Unimodal and Crossmodal working memory binding is not differentially affected by age or Alzheimer's disease

Unimodal and Crossmodal working memory binding is not differentially affected by age or Alzheimer's disease

Federica Guazzo[1-2] *, Richard Allen[3], Alan Baddeley[4], Sergio Della Sala[1]

[1]Human Cognitive Neuroscience, Psychology, University of Edinburgh, Edinburgh, UK

[2]Laboratory of Experimental Psychology, Suor Orsola Benincasa University, Naples, Italy

[3]School of Psychology, University of Leeds, Leeds, UK

[4]Department of Psychology, University of York, Heslington, York, UK

*Send correspondence to Federica Guazzo, Human Cognitive Neuroscience, Psychology, University of Edinburgh, 7 George Square, Edinburgh, EH8 9JZ, UK.

Email: s1584019@sms.ed.ac.uk

Acknowledgments

We acknowledge the support from the "Unitá operativa di valutazione Alzheimer" in the Distretto Sanitario di Mercato San Severino – Azienda Sanitaria Locale (ASL) Salerno, Italy. We thank all the clinicians, nurses, administrators, and staff in general, for having allowed us to recruit the AD patients involved in the present study.

Abstract

Working Memory Binding (WMB) entails the integration of multiple sources of information to form and temporarily store unique representations. Information can be processed through either one (i.e., Unimodal WMB) or separate sensory modalities (i.e., Crossmodal WMB). ***Objective:*** In this study, we investigated whether Crossmodal WMB is differentially affected by normal or pathological ageing compared to Unimodal WMB. ***Methods:*** Experiment 1: 26 older and 26 younger adults recalled the target feature matching the test probe to complete a previously displayed colour-shape binding (visually presented in the Unimodal condition; auditorily and visually presented in the Crossmodal condition). Experiment 2: 35 older and 35 younger adults undertook the same paradigm while carrying out articulatory suppression to limit verbal recoding. Experiment 3: 24 Alzheimer's Disease (AD) patients and two groups of 24 healthy matched controls (tested respectively with the same and an increased memory load compared to the patients) were recruited to perform a similar task. ***Results:*** Results show no age-related additional cost in Crossmodal WMB in respect to Unimodal WMB. AD patients had poor attainment in both WMB tasks regardless of specific binding condition. ***Conclusion:*** These findings provide evidence identifying WMB per se to be impaired in AD, regardless of the type of to-be-bound material. This supports the view that WMB is a suitable cognitive marker for AD.

Keywords: memory binding, working memory, Alzheimer's disease

Public Significance Statement

The experiments reported show that working memory binding deficits are typical of Alzheimer's disease independently of the modality of presentation, Unimodal binding or Crossmodal binding. The study demonstrates that it is the working memory binding mechanism per se to be impaired in Alzheimer's disease, and the reason why may be ascribed to the neural degeneration starting in the perirhinal cortex. The study further shows that both Unimodal and Crossmodal working memory binding are not differentially affected by healthy ageing.

Introduction

Working Memory Binding (WMB)[1] defines the cognitive function that mediates the association of multiple sources of information to form and temporarily store representations of the world (Luck & Vogel, 1997; Zimmer, Mecklinger, & Lindenberger, 2006). WMB can occur for different features (e.g., colour and shape, shape and location, words and sentences, etc.) across diverse domains (e.g., visual or verbal) and modalities (e.g., visual or auditory). *Unimodal WMB* accounts for the processing of information coming from multiple sources but in one single modality. Engaging separate sensory channels at the same time and elaborating incoming information in an integrated fashion (e.g., recognising an object from the sound it makes) entails a process known as *Crossmodal WMB*.

Within the field of cognitive ageing, researchers have become interested in Unimodal WMB mainly for two reasons: 1) To investigate whether a deficit to bind surface features (e.g., colour and shape) could contribute to the decline of (visual) WM observed across the life span (Brockmole & Logie, 2013; Johnson, Logie, & Brockmole, 2010); 2) To assess whether the memory deficits found in patients with Alzheimer's Disease (AD) for learned associations (Blackwell, Sahakian, Vesey, Semple, Robbins, & Hodges, 2004; Fowler, Saling, Conway, Semple, & Louis, 2002; O'Connell, Coen, Kidd, Warsi, Chin, & Lawlor, 2004; Swainson, Hodges, Galton, Semple, Michael, Dunn, Iddon, Robbins, & Sahakian, 2001) might also occur in WM (Cecchini, Yassuda, Bahia, de Souza, Guimarães, Caramelli, Carthery-Goulart, Patrocinio, Foss, Tumas, Lima-Silva, Brucki, Nitrini, Della Sala, & Parra, 2017; Della Sala, Parra, Fabi, Luzzi, & Abrahams, 2012; Parra, Abrahams, Fabi, Logie, Luzzi, & Della Sala, 2009a; Parra, Abrahams, Logie, & Della Sala, 2010a; Parra, Abrahams, Logie, Mendez, Lopera, & Della Sala, 2010b). Regarding the first purpose, several studies have concluded that older participants' memory for integrated colour-shape representations (i.e., conjunctions) is no more impaired than memory for features, compared to their younger counterparts (Brockmole, Parra,

[1] In this manuscript, we use the term 'Working Memory Binding' to discuss the same mechanism referred to as 'Short-Term Memory Binding' in prior neuropsychological and neuroimaging literature.

Della Sala, & Logie, 2008; Brown, Niven, Logie, Rhodes, & Allen, 2017; Parra, Abrahams, Logie, & Della Sala, 2009b; Rhodes, Parra, Cowan, & Logie, 2017). However, other studies reported that an age-related binding decline is indeed observable in WM (Brown & Brockmole, 2010, Exp.2; Isella, Molteni, Mapelli, & Ferrarese, 2015).

On the second point, several studies have reliably reported a specific impairment of AD patients in retaining visual colour-shape conjunctions for a limited period of time (Cecchini et al., 2017; Della Sala et al., 2012; Parra et al., 2009a; 2010a; 2010b). These studies concur in maintaining that the Unimodal WMB task is a reliable cognitive marker for the early detection of memory dysfunction in both the preclinical and clinical stages of AD (Parra et al., 2009a; 2010b).

Crossmodal WMB is a relatively novel concept. Studies so far have been conducted only in younger participants. Allen, Hitch, & Baddeley (2009; see also Gao, Wu, Qiu, He, Yang, & Shen, 2017) investigated how verbal and visual material is bound together to form unique, temporary mental representations. Younger adults were instructed to remember combinations of colours and shapes when: 1) presented as visual conjunctions; 2) sequentially presented as visually separated entities; 3) visual shapes were sequentially presented as blank outlines while colour names were delivered in synchrony through headphones; 4) coloured blobs were sequentially depicted on the screen while shape names were delivered auditorily. Participants had to judge whether the test probe, consisting of a visually presented coloured shape, matched a previous combination in each of the four above-mentioned conditions. Three concurrent tasks (i.e., articulatory suppression, spatial tapping, and backward counting) were used across three different experiments to gauge both Unimodal and Crossmodal WMB functions in recognition memory. Results showed that younger adults are able to bind features across modalities relying upon the same amount of attentional resources as for conjunctions engaging solely one sensory

channel at a time. However, very little is known about how Crossmodal WMB changes in healthy or pathological ageing.

Age-related changes in Crossmodal binding processing have so far been investigated in perceptual attention tasks, rather than in WM paradigms. In such perceptual paradigms, older adults benefit more from the provision of Crossmodal rather than Unimodal cues compared to their younger counterparts, especially when temporal congruency between the stimuli is at play (Brooks, Chan, Anderson, & McKendrick, 2018; Laurienti, Burdette, Maldjian, & Wallace, 2006; Mozolic, Hugenschmidt, Peiffer, & Laurienti, 2012; Peiffer, Mozolic, Hugenschmidt, & Laurienti, 2007). Decline in attention observed in healthy ageing appears to have the effect of encouraging multisensory integration, as older people are slower at distinguishing relevant from irrelevant stimuli and find it difficult to keep them separated (Alain & Woods, 1999; Guerreiro, Anguera, Mishra, Van Gerven, & Gazzaley, 2014; Robinson & Sloutsky, 2010; Talsma & Woldorff, 2005). However, this evidence does not endorse any conclusions on how older adults form and store Crossmodal conjunctive bindings in WM.

The perirhinal cortex has been identified as the neural site wherein perceptual material is bound across diverse modalities, as demonstrated by human and nonhuman primate research (Murray & Bussey, 1999; Murray & Richmond, 2001; Suzuki & Amaral, 1994; Taylor, Moss, Stamatakis, & Tyler, 2006; Tyler, Stamatakis, Bright, Acres, Abdallah, Rodd, & Moss, 2004). Throughout higher cognitive processing, and regardless of sensory channels, the role of the perirhinal cortex appears to be crucial to maintain bound representations in WM (Parra, Della Sala, Logie, & Morcom, 2014). Abnormal neurophysiological changes occur in the perirhinal cortex from very early stages of AD (Braak stages I-II), before hippocampal functioning is damaged (Didic, Barbeau, Felician, Tramoni, Guedj, Poncet, & Ceccaldi, 2011). Thus, Uni-modal WMB deficits have been shown in preclinical phases of AD (Parra et al., 2010b), and have been maintained to accurately discriminate between AD from other forms of dementia

(Cecchini et al., 2017; Della Sala et al., 2012). This evidence, together with the findings that healthy ageing does not affect Unimodal WMB (Parra et al., 2009a), supports the claim that Unimodal WMB deficits are sensitive and specific to AD. With regards to Crossmodal WMB, evidence from healthy younger adults showed that Crossmodal and Unimodal WMB are performed to equivalent accuracy and rely upon the same degree of attentional resources (Allen et al., 2009), possibly implying similar cognitive and neural mechanisms for the two tasks. However, there is currently a lack of behavioural studies comparing how these forms of binding might be affected by both healthy ageing and AD.

The experiments reported in this study present a twofold aim: 1) To investigate whether Crossmodal WMB is differently affected by age compared to Unimodal WMB; 2) To assess the effect of AD on Crossmodal WMB with respect to Unimodal WMB. Participants undertook the WMB tasks devised by Allen et al. (2009), but with two major modifications. Firstly, the number of experimental conditions was set to two instead of four, involving (i) the assessment of both visual unitised colour - shape and (ii) auditory colour – visual shape combinations. Secondly, the task was adapted to a cued-recall paradigm. We aimed to challenge participants' temporary binding capacities by employing a retrieval task wherein the study material is not re-presented in the test phase (Arenberg, 1973; Burke & Light, 1981; Craik, 1977; Craik & McDowd, 1987; Gajewski & Brockmole, 2006; Schonfield & Robertson, 1966), thus requiring participants to initiate an effortful mental search of the target stimulus to succeed (Craik, 1983; Hasher & Zacks, 1979). Experiment 1 and Experiment 2 addressed these premises by asking participants to carry out the tasks with and without Articulatory Suppression (AS). It is well known that age-related decremental effects are larger for visuospatial than for verbal WM (Jenkins, Myerson, Joerding, & Hale, 2000; Johnson et al., 2010), hence, we predicted that older adults might benefit from the use of verbal material when recalling the colour-shape bindings.

However, we expected that the prevention of verbal rehearsal by AS in Experiment 2 would cause a drop in the older group's accuracy.

Finally, Experiment 3 tested binding capacities in AD patients with both Unimodal and Crossmodal versions of the task. If single objects are formed through the binding mechanism and maintained as such in WM, we predicted that AD patients would show the same magnitude of impairment in carrying out any WMB tasks regardless of the modalities through which information is perceived and integrated. On the contrary, if the sensory features derived from distinct modalities are held in WM as separated entities, diverse cortical areas will be engaged to process auditory-visual rather than only visual material. As a result, AD patients will experience major difficulties in performing the Crossmodal WMB task compared to the Unimodal WMB task.

Methods

1. *Experiment 1*

Aims

Allen et al. (2009) demonstrated that younger participants are able to bind together colour and shape features across the visual and auditory modalities without requiring additional resources compared to the maintenance of visually presented combinations. Experiment 1 investigates whether there is evidence for an age-related Crossmodal binding decline in WM.

Ethics Statement

The current study was approved by the University of Edinburgh's Psychology Research Ethics Committee (Ref: 152-1718/8). All participants read the relevant information sheet and gave consent prior to participation.

Participants

Table 1 *– Demographics and average performance on the MMSE of the two groups of participants in Experiment 1.*

	Younger (N = 26)		**Older** (N = 26)		**T-test**
	M	SD	M	SD	T(50), p
Age	18.57	.59	71.38	5.47	48.15, <.001
Years of Education	13.52	.58	15.30	2.31	3.45, .001
MMSE	28.73	1.48	29.34	1.09	1.53, .13
(range)	(25 - 30)		(26 – 30)		
Sex	5 men; 21 women		13 men; 13 women		

Following an *a priori* power analysis, based on a mixed ANOVA design with an effect size of .37 (as in Brown et al., 2017, Experiment 1) and power at .80 (G*Power 3.0.10; Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007), twenty-six younger adults (YA) and twenty-six older adults (OA) took part in the experiment receiving either course credit or an honorarium. Younger participants were students from the University of Edinburgh, whereas older adults were recruited from the university volunteer panel. They were Europeans and Asians, and demographics are reported in *Table 1*. Participants had no known auditory problems, had normal or corrected-to-normal vision. The Mini Mental State Examination (MMSE - Folstein, Folstein, & McHugh, 1975) indicated that none of the participants showed signs of cognitive impairment (see *Table 1*).

Materials and apparatus

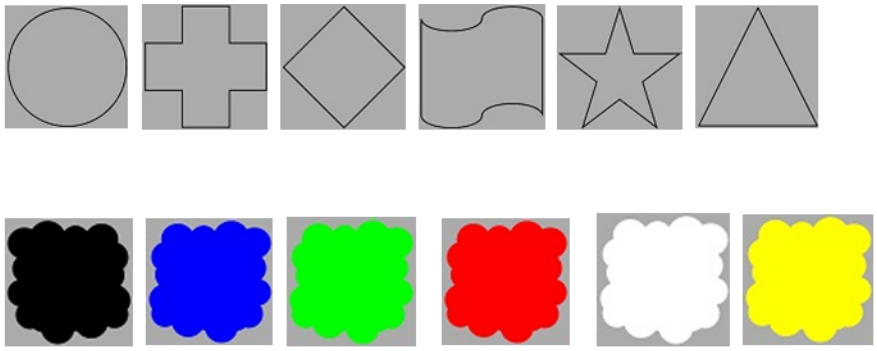

Fig. 1 *- Experimental stimuli – Coloured blobs and blank shapes taken from Allen et al., 2006.*

Visual stimuli utilised a set of six simple shapes (circle, cross, diamond, star, flag, triangle) and six colours (green, red, blue, yellow, black, white) derived from Allen, Baddeley, & Hitch (2006; see *Figure 1*). Two changes were made compared to the original pool of material: 1) Among the colours, 'white' was used instead of 'grey', since all stimuli were presented against a grey background; 2) Only the more easily nameable items, selected on the basis of the results obtained by Allen et al. (2006) when testing for ease of discriminability, were included. Each colour was depicted as a formless shape (i.e., a 'blob') while each shape was displayed as an unfilled black outline. All visual stimuli were displayed at the centre of the screen, with an item' size of 124 x 124 mm and subtending a visual angle of approximately 17°. Auditory stimuli were obtained from the website http://www.fromtexttospeech.com/ by converting text files into recordings. A male English voice (British accent) was used, and the material was presented via headphones. Arrays were made of three items presented one by one. The choice of using a set size three was in accord to previous studies (Allen et al., 2009; Brown & Brock-mole, 2010) accounting for the assessment of healthy participants' WMB capacities. Testing was controlled on a Macintosh iMac with a 13.5-inch screen, placed at approximately 40 cm from the subject, and 'PsychoPy' program (version 1.85.1 - Peirce, 2007; 2009) was used to run the experiment.

.Design and procedure

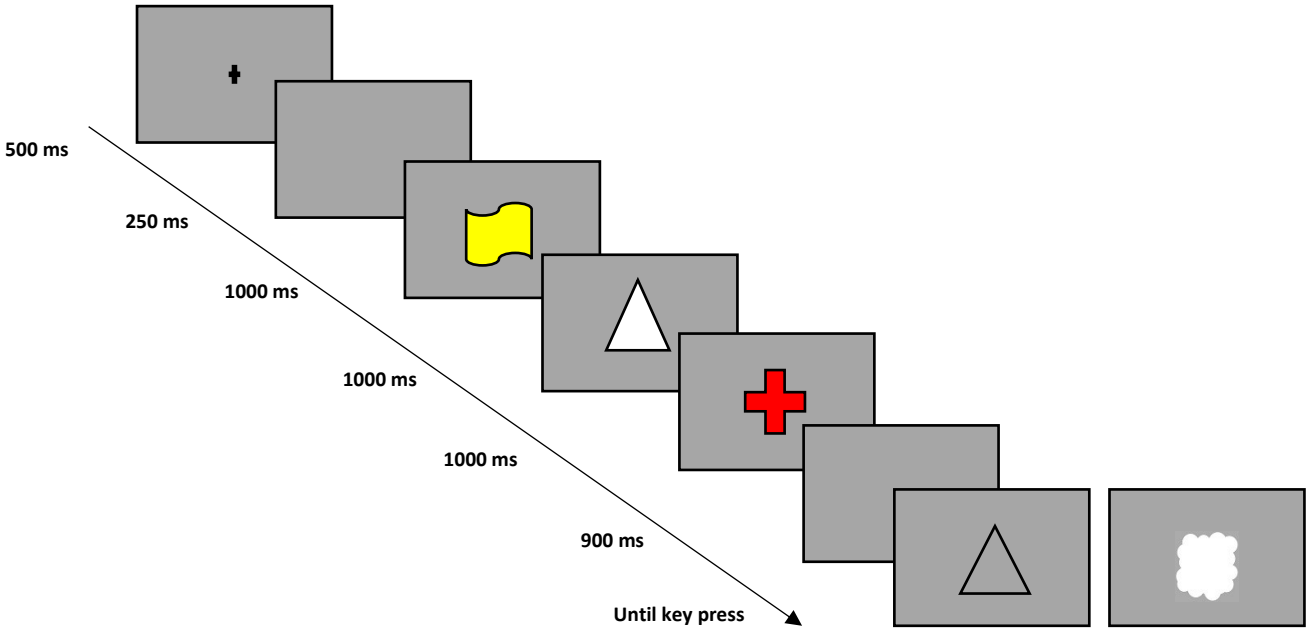

Fig. 2 *- Example of a trial run in the Unimodal condition. After observing the series of three visual colour-shape bindings appearing on the computer screen, participants were instructed to recall the missing feature as soon as the cue (i.e., either the unfilled shape or the coloured blob) was displayed. In the Crossmodal condition the procedure was the same, with the three blank shapes visually presented and the three colour names delivered through headphones.*

The experiment followed a 2x2 mixed design, with age group (Older; Younger) as the between-subjects factor and binding condition (Unimodal; Crossmodal) as the within-subjects factor. In the *Unimodal condition*, a series of three visual colour-shape conjunctions was presented in sequence on the computer screen. In the *Crossmodal condition*, a series of three blank shapes was visually presented while three colour names were delivered in synchrony through headphones. In each case, after a brief delay, either a shape or a colour probe appeared. Participants were instructed to recall the feature that was originally paired with the test probe feature.

At the beginning of the experiment, both age groups were screened for potential colour vision deficiency. They were presented with two separate arrays, one consisting of the six experimental shapes and the other consisting of the six experimental colours. They were asked to name the stimuli one by one in order to ensure that every feature was known and recognised. The experimental session then started. Each experimental trial began with a fixation cross displayed at the centre of the screen for 500ms, followed by a 250ms blank screen delay. Each visual item was presented at the screen centre for 1000ms. A 900ms blank screen delay followed the presentation of the three feature pairs. The test probe was then shown at the centre of the screen. *Figure 2* illustrates the example of a trial run. On 50% of the trials, the shape was the to-be-recalled feature, whereas, on the remaining 50% of the trials it was the colour to be recollected. This occurred in a randomly intermixed fashion. Conditions were blocked and their order was counterbalanced. Responses were recorded through a microphone. There was no limit on the time available to recall the information. Participants could perform the tasks at their own pace by pressing space bar when they were ready to proceed with the following trial. Nonetheless, they were explicitly invited to take a break twice throughout the session. Each block consisted of 6 practice trials and 36 test trials divided in two blocks of 18 trials each. This allowed the three serial positions to be tested the same amount of times in both conditions. Conjunctions were repeated within the same block but not within the same array[2].

Data Analysis

Percentage of correct responses as well as errors were analysed through mixed ANOVAs by means of both frequentist (alpha level set at .05) and Bayes Factor (BF) analyses. Frequentist

[2] A pilot study was conducted prior to the experiment to ascertain that participants were able to recognise and name all the colours and shapes used as experimental stimuli. Moreover, it checked the possibility that the tasks could have been too difficult to perform. Nine healthy younger adults (Age: M=29.66, SD=3.04; YoE: M=18.44, SD=.52; 6 men and 3 women) were tested with the WMB tasks. Results from a paired sample t-test revealed that the performance in the Unimodal condition (M=.83, SD= .13) and that in the Crossmodal condition (M= .79, SD= .10) were not significantly different ($t(8)$= -.99, p= .34, d= .32).

analysis was run in R Studio (version 1.1.456; R Core Team, 2013) and IBM SPSS Statistics 21, whereas BF analysis was run in JASP (version 0.9.2; JASP Team, 2019). BF analysis quantifies the predictive strength of the alternative hypothesis (H1) compared to the null hypothesis (H0). All possible models were assessed by accounting for interactions even when the main effect was not included. The inclusion BF, 'BF', indicates the extent to which the data support inclusion of the factor of interest, taking all models into account. BF_{10} indicates the likelihood of H1 over H0, and the larger BF_{10} the greater support for H1. BFs for all main effects and interactions are reported afterwards. The default priors were set as described in Rouder, Morey, Speckman and Province (2012), and the number of iterations was set at 500,000 to guarantee a smaller percentage of errors.

Results

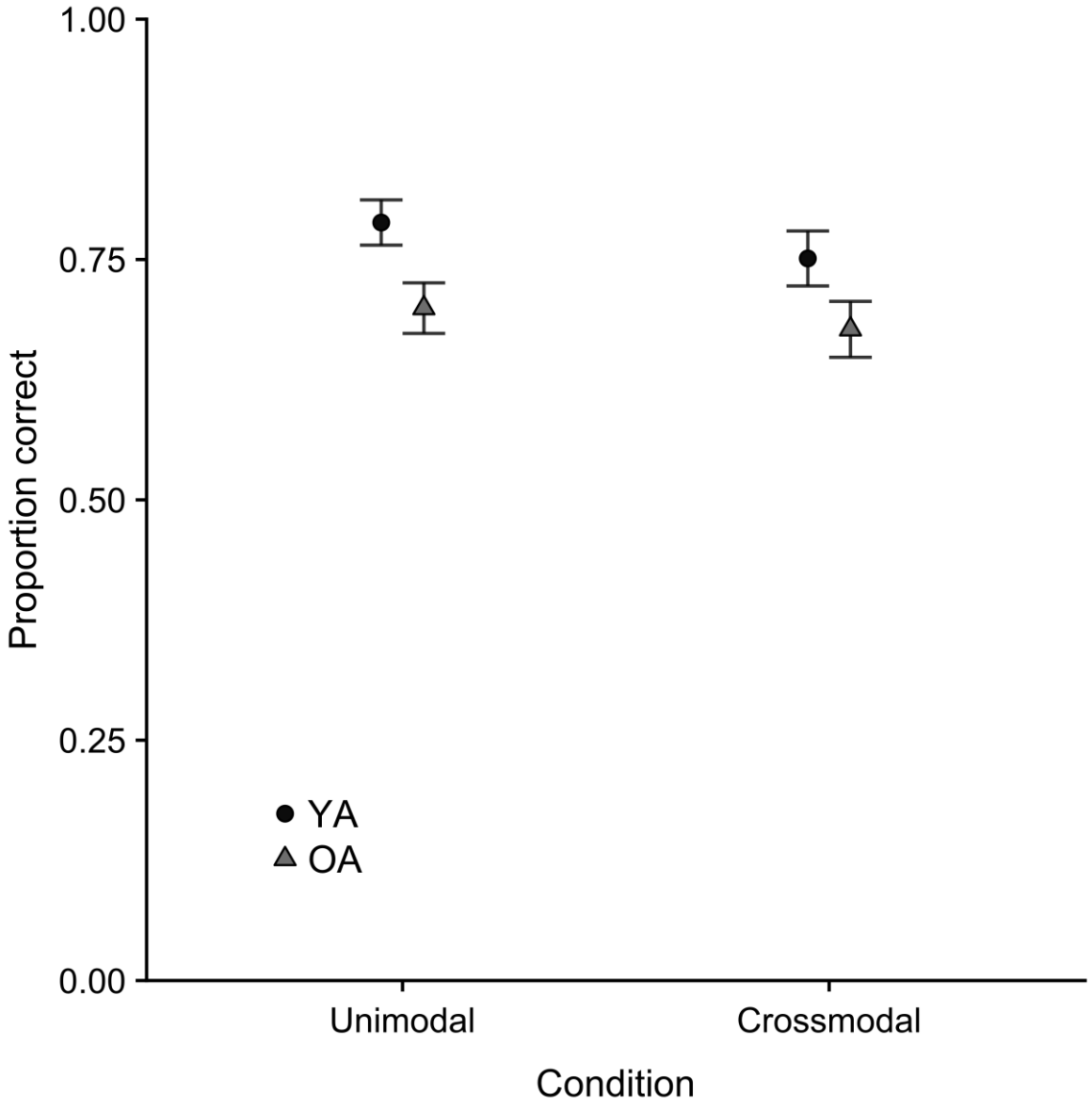

Fig. 3 *- Percentage of correct responses in the Unimodal and Crossmodal conditions for both younger and older adults.*

Accuracy. A 2 (Unimodal condition vs Crossmodal condition, within factor) x 2 (Older adults vs Younger adults, between factor) mixed ANOVA yielded no significant effect of condition ($F(1,50)= 3.05$, $p= .08$, $\eta^2p= .05$, $BF= .78$). *Figure 3* illustrates the significant age effect ($F(1,50)= 5.68$, $p= .02$, $\eta^2p= .10$, $BF= 3$), showing a higher accuracy level for younger adults compared to older adults in both Unimodal (YA: $M= .78$, $SD= .11$; OA: $M= .69$, $SD=$

.13) and Crossmodal (YA: M= .75, SD= .14; OA: M= .67, SD= .14) conditions. No interaction effect was found (F(1,50)= .20, p= .65, η^2p= .004, BF= .30). These results were supported by the BF analysis, showing that the most likely model to explain our data included the main effect of group (BF_{10}= 2.83 relative to the null model including only participant).

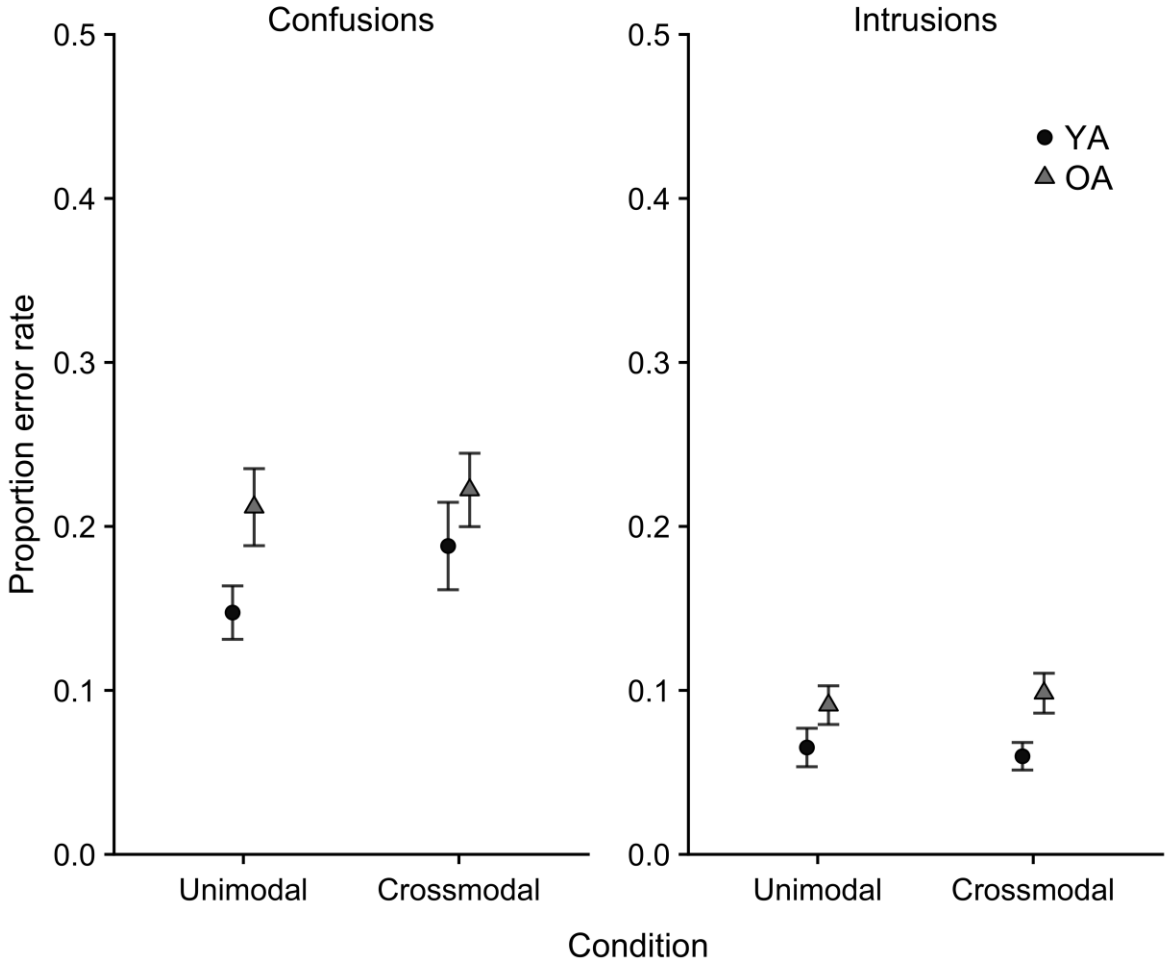

Fig. 4 *- Rates of within-series confusions and extra-series intrusions for both age groups in both binding conditions.*

Error Analysis. This analysis was conducted in order to investigate what type of errors participants were more inclined to make. Error types were divided into two categories, based on Hu, Hitch, Baddeley, Zang, and Allen (2014): 1) *Within-series confusions*, participants recalled a feature from the to-be-studied array that did not match with the test probe. These errors can be considered as reflecting an error in WMB; 2) *Extra-series intrusions*, participants recalled a feature that was not displayed in the to-be-studied array.

A 2 (Unimodal condition vs Crossmodal condition, within factor) x 2 (Older adults vs Younger adults, between factor) mixed ANOVA on within-series confusions revealed no significant main effect of condition ($F(1,50)= 2.29$, $p= .13$, $\eta^2p= .04$, $BF= .44$) as well as of group ($F(1,50)= 3.32$, $p= .07$, $\eta^2p= .06$, $BF= .89$); furthermore, no condition*group interaction ($F(1,50)= .79$, $p= .37$, $\eta^2p= .01$, $BF= .28$) was found. All participants were equally prone to recalling a feature not matching the test probe but belonging to the same visual array across both experimental conditions. According to BF analysis, the most likely model included the main effect of group ($BF_{10}= 1.12$ relative to the null model including only participant).

In addition, a 2x2 mixed ANOVA on extra-series intrusions yielded a significant main effect of group ($F(1,50)= 6.70$, $p= .01$, $\eta^2p= .11$, $BF= 2.49$): older adults made a higher extra-series intrusions rate compared to their younger counterparts, and this held true in both Unimodal (YA: $M= .06$, $SD= .05$; OA: $M= .09$, $SD= .06$) and Crossmodal (YA: $M= .05$, $SD= .04$; OA: $M= .09$, $SD= .06$) conditions. Main effect of condition ($F(1,50)= .01$, $p= .92$, $\eta^2p= .0002$, $BF= .17$) and condition*group interaction ($F(1,50)= .42$, $p= .51$, $\eta^2p= .008$, $BF= .17$) were not significant. As before, the most likely model included main effect of group ($BF_{10}= 4.43$ relative to the null model including only participant). *Figure 4* shows the proportion of errors made by both younger and older adults in both conditions.

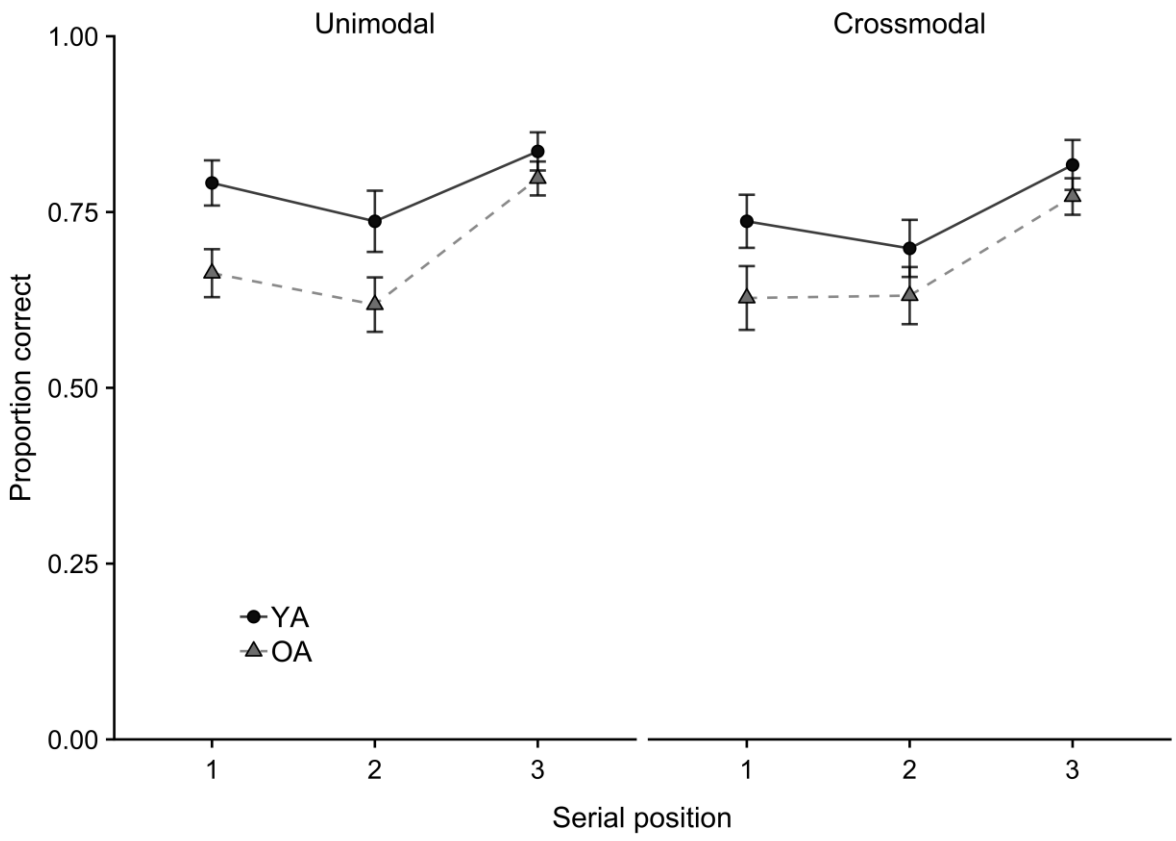

Fig. 5 *– Proportion correct across serial positions for each age group and task condition.*

Serial Position Analysis. The last supplementary analysis aimed to assess the percentage of correct responses for each serial position (SP) in both experimental conditions. A 2 (Unimodal condition vs Crossmodal condition, within factor) x 3 (SP1 vs SP2 vs SP3, within factor) x 2 (Older adults vs Younger adults, between factor) mixed ANOVA yielded a main effect of serial position ($F(2, 100)= 17.31$, $p< .001$, $\eta^2p= .25$, $BF> 10{,}000$). *Figure 5* shows the recall rates in both the Unimodal and Crossmodal conditions (see also *Supplementary Material*, *Table 1*). There was a significant difference due to age ($F(1,50)= 6.20$, $p= .01$, $\eta^2p= .11$, $BF= 2.95$) as seen previously. The effect of condition was not significant ($F(1,50)= 2.41$, $p= .12$, $\eta^2p= .04$, $BF= .40$), and no two-way or three-way interactions were found ($p= .26$, $\eta^2p= .02$, $BF= .28$). The BF analysis indicated that the most likely model was the one including the main effect of

group and SP, as well as the group*condition interaction (BF_{10}> 10,000 relative to the null model including only participant).

Discussion

Experiment 1 revealed the expected age effect on cued recall, with older participants being less accurate than their younger counterparts in both experimental conditions. However, the performance in the Crossmodal condition did not differ significantly from that in the Unimodal condition, for both older and younger adults. This suggests that age does not have any differential effect on Crossmodal relative to Unimodal WMB. The error analysis showed a common trend to recall a feature presented in the study sequence but not matching the test probe (i.e. a WMB error) that emerged throughout the tasks, and that was elevated in the older adult group. Finally, the serial position analysis highlighted a general tendency for improved recall of the final item in the sequence in both conditions, as previously observed in Allen et al.' studies (Allen, Baddeley, & Hitch, 2006; 2014).

2. *Experiment 2*

Aims

All colours and shapes used in the WMB tasks in Experiment 1 were potentially nameable. This may have elicited recoding and rehearsal of the information as a strategy for better recall, a mechanism that is possibly more prominent in younger adults (Brown & Wesley, 2013; Bunce & Macready, 2005). Experiment 2 was carried out in order to address the possibility that overt repetition of the item names could have modulated the performance of either younger or older adults.

Participants

Table 2 *– Demographics and average scores in the MMSE for Experiment 2.*

	Younger (N = 35)		**Older** (N = 35)		**T-test**
	M	SD	M	SD	T(68), p
Age	18.60	.84	68.11	11.24	25.97, <.001
Years of Education	13.42	.73	15.60	1.73	6.81, <.001
MMSE	29.22	.80	29.17	1.29	-.22, .82
(range)	(27 - 30)		(25 - 30)		
Sex	11 men; 24 women		8 men; 27 women		

Thirty-five younger adults and thirty-five older adults were recruited for this experiment receiving either course credit or an honorarium. They were Europeans and Asians, and none of them had participated in Experiment 1. Demographics of the two age groups are reported in *Table 2*. Younger participants were students from the University of Edinburgh, whereas older adults were recruited from the university volunteer pool. Participants had no known auditory problems, had normal or corrected-to-normal vision. The MMSE (Folstein et al., 1975) indicated that no participants showed signs of cognitive impairment (see *Table 2*).

Materials and procedure

Material and experimental procedure were the same as in Experiment 1, except for the use of articulatory suppression (AS). Participants were instructed to repeat the digits "*one, two, three, four*" constantly and aloud from the first fixation cross at the beginning of the study display until the appearance of the test probe. The text message "*Repeat out loud: "ONE, TWO, THREE, FOUR". Press SPACE to go on"* reminded them to do so before starting every new experimental trial. Furthermore, each session was monitored to ensure that this occurred and the experimenter occasionally reminded participants to verbally rehearse the digits as well.

Data Analysis

Both frequentist and Bayes Factor data analyses were conducted in R Studio (version 1.1.456; R Core Team, 2013), IBM SPSS Statistics 21, and JASP (version 0.9.2; JASP Team, 2019). Percentage of correct responses as well as errors were analysed by means of mixed ANOVAs. Bonferroni pairwise comparisons were used to examine further specific differences between groups in the two experimental conditions.

Results

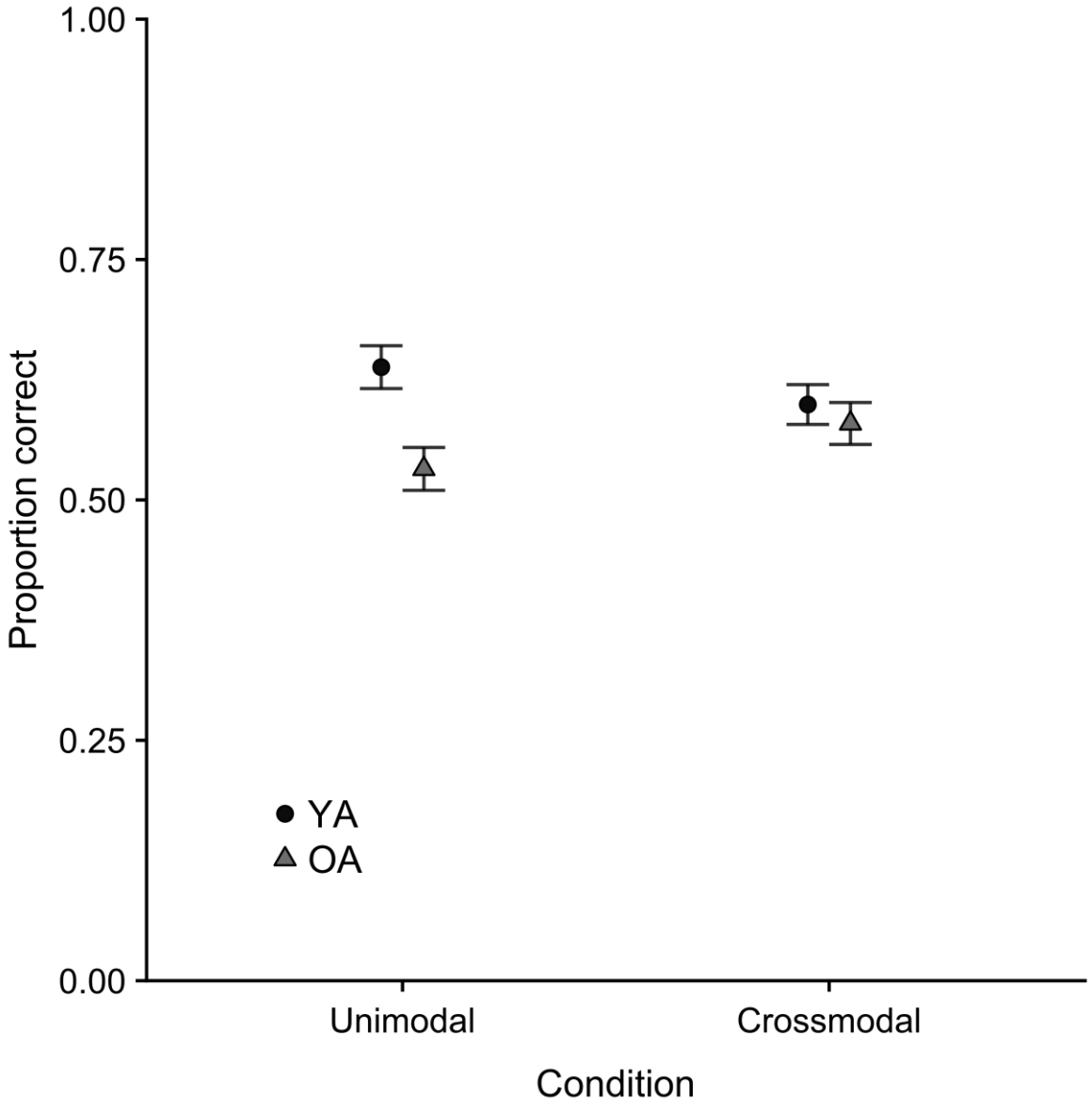

Fig. 6 *– Level of accuracy in the Unimodal and Crossmodal conditions reached by both younger and older adults.*

Accuracy. A 2x2 mixed ANOVA showed no main effect of condition ($F(1,68)= .06$, $p= .79$, $\eta^2p= .001$, $BF= .18$); there was a main effect of group ($F(1,68)= 5.70$, $p= .02$, $\eta^2p= .07$, $BF= 2.79$) on the performance instead. A condition*group interaction ($F(1,68)= 7.19$, $p= .009$, $\eta^2p= .09$, $BF= 5.04$) was also found (see *Figure 6*). Bonferroni pairwise comparisons reported that younger and older adults were significantly different at performing the Unimodal condition (YA: $M= .63$, $SD= .13$; OA: $M= .53$, $SD= .13$; $t(68)= -3.35$, $p< .001$, $d= -.80$, $BF_{10}= 24.83$) but not the Crossmodal condition (YA: $M= .59$, $SD= .12$; OA: $M= .57$, $SD= .12$; $t(68)= -.65$, $p= .51$, $d= -.15$, $BF_{10}= .29$). BF analysis indicated the model comprising the main effect of group as the most likely one ($BF_{10}= 2.80$ relative to the null model including only participant).

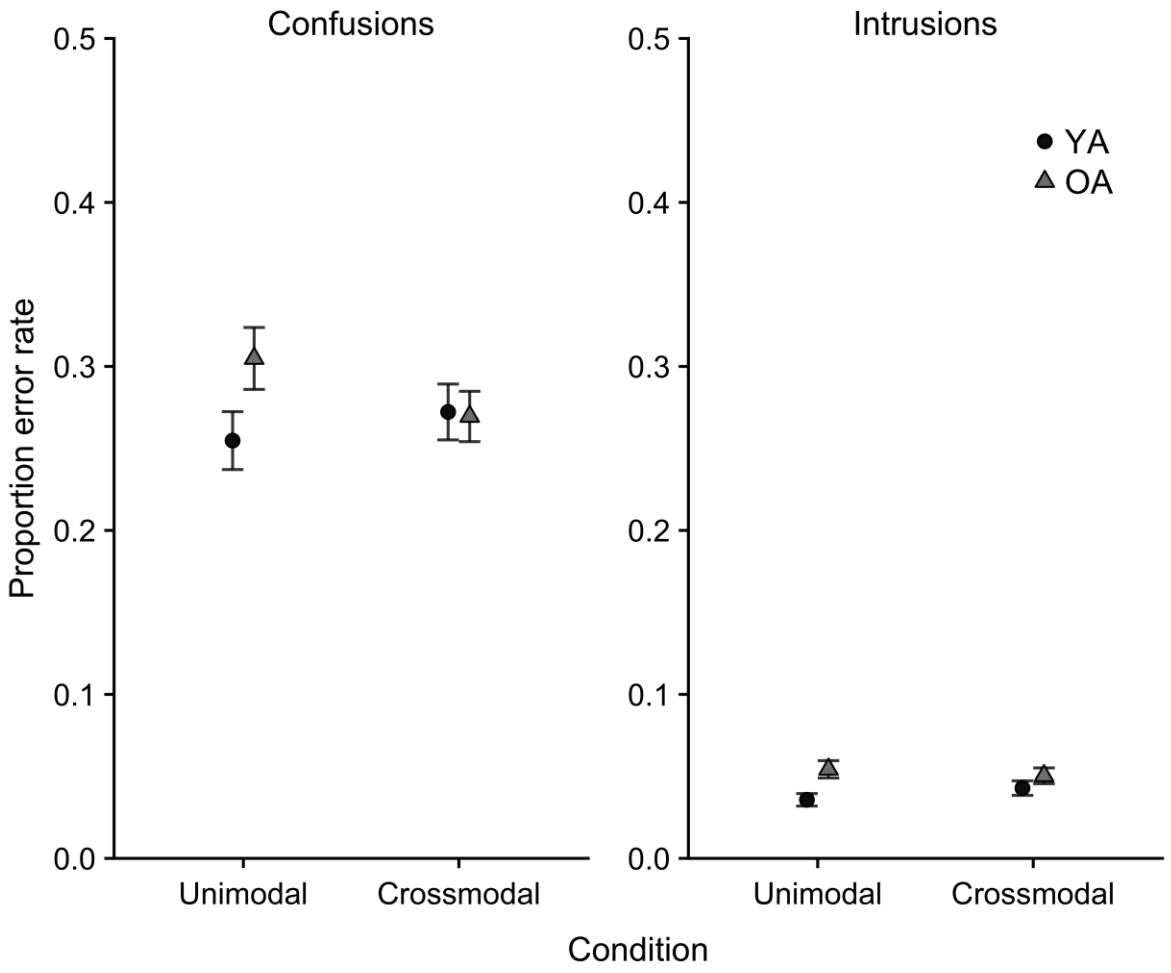

Fig. 7 *- Percentage of within-series confusions and extra-series intrusions made by younger and older participants in both binding conditions.*

Error Analysis. Types of error were classified as in Experiment 1 and percentages of within-series confusions and extra-series intrusions for both age groups and conditions are depicted in *Figure 7*.

A 2x2 mixed ANOVA on within-series confusions reported neither significant effect of condition ($F(1,68)= .38$, $p= .53$, $\eta^2p= .006$, $BF= .21$) nor group ($F(1,68)= 1.43$, $p= .23$, $\eta^2p= .02$, $BF= .43$). Also, a significant condition*group interaction ($F(1,68)= 3.38$, $p= .07$, $\eta^2p= .04$, $BF= 1.04$) was not found. On average, older adults made the same amount of within-series

confusions as their younger counterparts in both Unimodal (YA: M= .25, SD= .10; OA: M= .30, SD= .11) and Crossmodal (YA: M= .27, SD= .10; OA: M= .26, SD= .09) conditions. The BF analysis revealed that the most likely model accounted for the main effect of group (BF_{10}= .43 relative to the null model including only participant).

Analysis on extra-series intrusions yielded no significant main effect of condition ($F(1,68)$= .16, p= .68, η^2p= .002, BF= .19) and no condition*group interaction ($F(1,68)$= 2.02, p= .16, η^2p= .02, BF= .61). The effect of group was significant ($F(1,68)$= 6.19, p= .01, η^2p= .08, BF= 2.96): overall, older adults recalled more features presented across the tasks but not in the to-be-studied array compared to younger participants in both Unimodal (YA: M= .03, SD= .02; OA: M= .05, SD= .03) and Crossmodal (YA: M= .04, SD= .02; OA: M= .05, SD= .02) conditions. The most likely model, as indicated by the BF analysis, was the one including the main effect of group (BF_{10}= 2.95 relative to the null model including only participant).

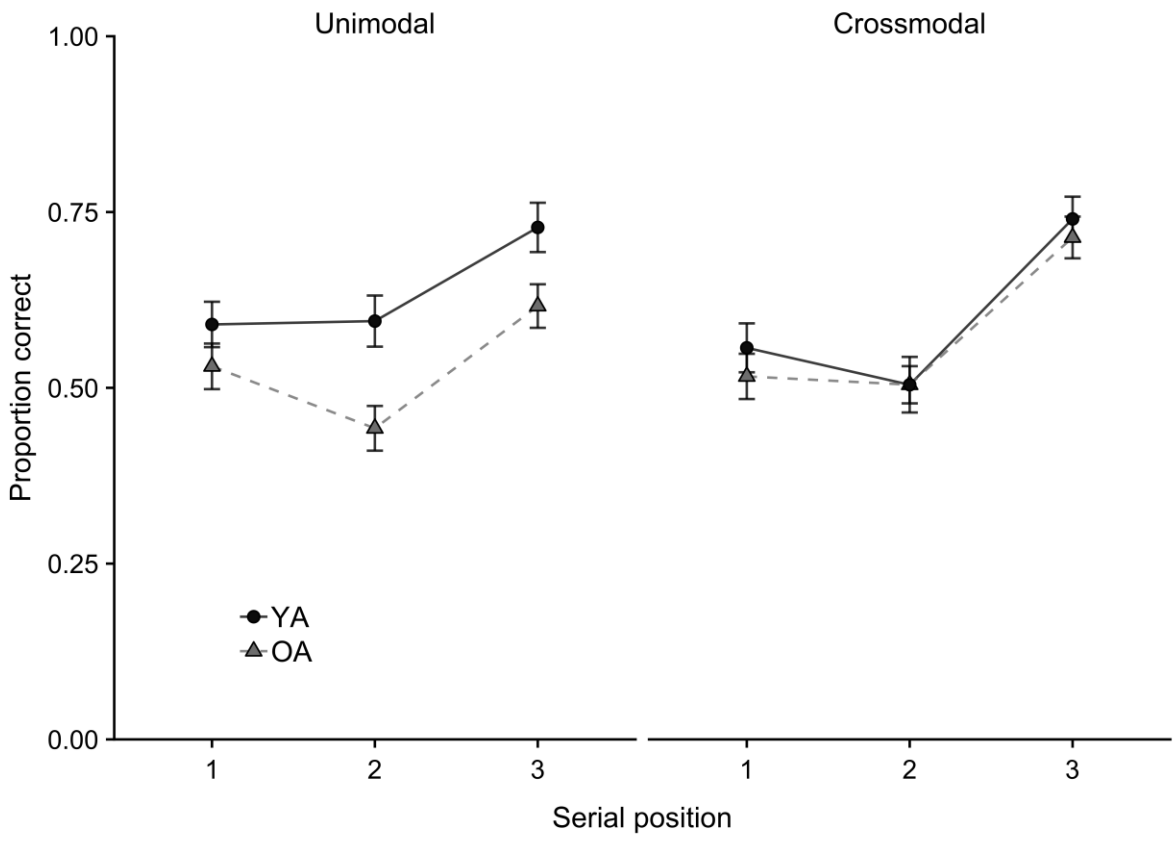

Fig. 8 *– Correct responses (%) across serial positions for each age group and task condition.*

Serial Position Analysis. A further analysis on serial position was carried out as in Experiment 1. A2x3x2 mixed ANOVA presented a significant effect of serial position ($F(2,136)= 38.43$, $p< .001$, $\eta^2p= .36$, $BF> 10,000$). A main effect of group ($F(1,68)= 6.12$, $p= .01$, $\eta^2p= .08$, $BF= 2.24$) was also verified, since older adults recalled less than younger adults (see *Figure 8*; see also *Supplementary Table 2*). The main effect of condition was not significant ($F(1,68)= .11$, $p= .73$, $\eta^2p= .002$, $BF= .11$), but a condition*group interaction was found ($F(1,68)= 7$, $p= .01$, $\eta^2p= .09$, $BF= 2.48$). Post-hoc t-tests yielded a significant difference between older and younger adults when recalling Unimodally processed items presented in SP2 ($t(68)= -3.15$, $p= .002$, $d= -.75$, $BF_{10} = 14.85$) and SP3 ($t(68)= -2.39$, $p= .02$, $d= -.57$, $BF_{10}= 2.69$). Items presented in SP1 were equally recollected from both groups ($t(68)= -1.30$, $p= .19$, $d= -.31$, $BF_{10}= .50$). On the

contrary, in the Crossmodal condition, there were no significant differences between younger and older participants independently of the serial position of each binding: SP1 ($t(68)= -.85$, $p= .39$, $d= -.20$, $BF_{10}= .33$), SP2 ($t(68)= .002$, $p= .99$, $d= .004$, $BF_{10}= .24$), SP3 ($t(68)= -.60$, $p= .54$, $d= -.14$, $BF_{10}= .28$). Neither two-way nor three-way interactions were revealed ($p= .10$, $\eta^2p= .03$, $BF= .31$). Both main effect of group and SP were included in the most likely model, as well as the interaction between SP and condition ($BF_{10}> 10,000$ relative to the null model including only participant).

Discussion

Experiment 2 confirmed the age-related decline previously revealed and, in addition, an interaction effect was found. Older and younger adults significantly differed in the Unimodal condition only, especially when visual bindings were presented in SP2 and SP3 within the study array. As before, the error analysis corroborated the tendency to swap the features within the study items when recalling, suggesting the occurrence of WMB errors. The serial position curve highlighted a trend to better remember the last conjunction of the series across conditions.

Cross-Experiment Analysis. Finally, a 2 (Unimodal condition vs Crossmodal condition, within factor) x 2 (AS vs No AS, between factor) x 2 (Older adults vs Younger adults, between factor) mixed ANOVA tested the role of preventing participants' overt rehearsal on their performance. Condition did not appear to be a significant factor ($F(1,118)= 1.16$, $p= .28$, $\eta^2p= .01$, $BF= .19$), whereas group ($F(1,118)= 11.58$, $p< .001$, $\eta^2p= .08$, $BF= 31.05$) and AS ($F(1,118)= 44.84$, $p< .001$, $\eta^2p= .27$, $BF> 10,000$) were both significant. The latter finding indicates that AS led to reduced accuracy overall. Nonetheless, a group*AS interaction was not found ($F(1,118)= .19$, $p= .66$, $\eta^2p= .002$, $BF= .35$), suggesting that both groups performed worse when AS was required despite their age. Results also yielded a condition*group interaction ($F(1,118)= 4.57$, $p= .03$, $\eta^2p= .03$, $BF= 1.94$), and Bonferroni comparisons confirmed that older

and younger adults showed a significantly different performance in the Unimodal ($t(120)= -3.60$, $p< .001$, $d= -.65$, $BF_{10}= 56.64$) but not in the Crossmodal ($t(120)= -1.59$, $p= .11$, $d= -.28$, $BF_{10}= .60$) conditions. Any other interaction was not significant ($p= .13$, $\eta^2p= .01$, $BF= .69$). The most likely model included the main effect of AS and the condition*AS interaction ($BF_{10}>$ 10,000 relative to the null model including only participant).

This cross-experiment comparison demonstrates that both younger and older adults were challenged by the prevention of overt rehearsal of the stimuli to the extent that the overall accuracy decreased from the first to the second experiment.

3. Experiment 3

Aims

Experiment 3 investigates whether patients in the mild to moderate stages of AD are able to hold bound information coming from diverse sensory modalities in WM. It also investigates whether any deficit in maintaining Crossmodally bound features would reflect an impairment over and above temporary memory problems for conjunctive binding as tested solely within the visual domain (Cecchini et al., 2017; Della Sala et al., 2012; Parra et al., 2009a; 2010b).

Participants

Table 3 *– Demographics of participants in Experiment 3.*

	AD (N = 24)		**Older (set size 2)** (N = 24)		**Older (set size 3)** (N = 24)		**T-test T(46), p**		
	M	SD	M	SD	M	SD	AD vs OA2	AD vs OA3	OA2 vs OA3
Age	76.29	5.18	74.54	4.12	74.75	3.92	1.29, .20	-1.16, .25	.17, .85
Years of Education	9.08	1.18	10.20	3.47	9.56	2.90	-1.29, .20	.70, .48	-.63, .52
Sex	13 men; 11 women		9 men; 15 women		11 men; 13 women				

According to an *a priori* power analysis based on Experiment 1 (G*Power 3.0.10; Faul et al., 2009; 2007), twenty-four AD patients and forty-eight older adults (OA) undertook the WMB tasks. All participants were Europeans. Patients were diagnosed with AD dementia according to the diagnostic criteria established by the DSM-IV-TR, and the National Institute of Neurological and Communicative Disorders and Stroke (NINCDS), and the Alzheimer's Disease and Related Disorders Association (ADRDA) workgroups (McKhann, Drachman, Folstein, Katzman, Price, & Stadlan, 1984; McKhann, Knopman, Chertkow, Hyman, Jack, Kawas, Klunk, Koroshetz, Manly, Mayeux, Mohs, Morris, Rossor, Scheltens, Carrillo, Thies, Weintraub, & Phelps, 2011). They were recruited at the "Unitá operativa di valutazione Alzheimer" in the Distretto Sanitario di Mercato San Severino – Azienda Sanitaria Locale (ASL) Salerno, Italy. Among forty-eight healthy controls, three were spouses and two were carers of the patients while the others were recruited through word of mouth. They were divided in two groups of twenty-four subjects each (i.e. OA2 and OA3) in order to account for a diverse experimental manipulation. Specifically, OA2 performed the tasks with the same set size as AD patients, whereas OA3 were shown an increased set size. The three groups were matched for age and years of education, and demographics are reported in *Table 3*. Participants had no known auditory problems, and normal or corrected-to-normal vision. They were screened for colour blindness by asking them for naming the stimuli before the starting of the experimental session, as explained previously (see *Design and Procedure* in *Experiment 1*). Reading the information sheet and giving written consent were necessary steps to fulfil prior to participation.

Neuropsychological Assessment

Table 4 *– Neuropsychological profile of AD patients, OA2, and OA3 in Experiment 3.*

	Cut-off score	AD (N=24)	OA2 (N=24)	OA3 (N=24)	T-test T(46), p		
		M ± SD (range)	M ± SD (range)	M ± SD (range)	AD vs OA2	AD vs OA3	OA2 vs OA3
GDS	< 9	10 ± 8.26 (1 - 28)	8.45 ± 5.90 (1 - 24)	16 ± 2.82 (1 - 18)	.69, .49	1.21, .23	.66, .51
ACE	< 82	44 ± 15.84 (13 - 59)	89.37 ± 6.31 (82 - 100)	90.63 ± 5.19 (82 - 100)	-14.37, <.001	-15.20, <.001	-.74, .45
MMSE	< 23	16.60 ± 6.38 (8 - 22)	28.12 ± 1.91 (24 - 30)	28.38 ± 1.27 (26 - 30)	-10.09, <.001	-10.66, <.001	-.53, .59
FAS	-[a]	10.50 ± 7.46 (0 - 26)	38.58 ± 15.70 (20 - 73)	35.13 ± 9.79 (20 - 56)	-7.62, <.001	-9.52, <.001	.91, .36
SEMANTIC FLUENCY	< 7	5.41 ± 1.60 (2.25 – 6)	17.07 ± 4.19 (12 - 30)	16.60 ± 3.75 (12 - 27)	-12.28, <.001	-13.06, <.001	.48, .63
FCSRT-IFR	-[b]	6.87 ± 6.41 (0 - 17)	27.75 ± 3.92 (20 - 35)	25.71 ± 5.08 (19 - 35)	-13.62, <.001	-10.78, <.001	1.62, .11
FCSRT-ITR	< 35	19.95 ± 12.59 (0 - 33)	35.87 ± .33 (35 – 36)	35.71 ± .46 (35 - 36)	-6.18, <.001	-6.12, <.001	1.42, .16
DIGIT SPAN	< 4	2.95 ± 1.11 (0 - 3)	5.58 ± 1.05 (4 - 7)	5.13 ± .74 (4 - 6)	-8.10, <.001	-7.77, <.001	1.73, .08
ADL		2.25 ± 1.77 (1 - 5)					

GDS= Geriatric Depression Scale; ACE= Addenbrooke's Cognitive Examination; MMSE= Mini Mental State Examination; FCSRT= Free and Cued Selective Reminding Test; IFR= Immediate Free Recall; ITR= Immediate Total Recall; ADL= Activities of Daily Living

[a] Equivalent scores: 0 (0 – 17.35), 1 (17.36 – 21.33), 2 (21.34 – 25.16), 3 (25.17 – 30.41), 4 (> 30.42)

[b] Equivalent scores: 0 (0 – 19.59), 1 (19.60 – 22.53), 2 (22.54 – 25.46), 3 (25.47 – 28.40), 4 (28.41 - 36)

AD patients underwent a neuropsychological assessment in order to characterise the sample. The same neuropsychological battery was administered to healthy controls to test all groups under the same circumstances. The neuropsychological battery comprised tests of global cognitive functioning (Addenbrooke's Cognitive Examination-Revised, ACE-R– Mioshi, Dawson, Mitchell, Arnold, & Hodges, 2006; Siciliano, Raimo, Tufano, Basile, Grossi, Santangelo, Trojano, & Santangelo, 2016); memory (Free and Cued Selective Reminding Test, FCSRT - Frasson, Ghiretti, Catricalà, Pomati, Marcone, Parisi, Rossini, Cappa, Mariani, Vanacore, & Clerici, 2011; Grober & Buschke, 1987); attention (Digit Span forward – Orsini, Trojano, & Chiacchio, 1988); verbal fluency (FAS - Borkowski, Benton, & Spreen, 1967; Word Fluency: Colours, Animals, Fruit, Cities – Spinnler & Tognoni, 1987); depressive symptoms (Geriatric Depression Scale, GDS – Brink, Yesavage, Lum, Heersema, Adey, & Rose, 1982). AD patients' carers were also asked to respond to the Activities of Daily Living (ADL) questionnaire

(Katz, Ford, Moskowitz, Jackson, & Jaffe, 1963). The neuropsychological profile of participants who entered the study is shown in *Table 4*.

Materials and apparatus

The experimental material and apparatus were the same as in Experiment 1 and 2. Visual stimuli utilised a formless shape (i.e., a 'blob') to depict the colours and unfilled three-point black outline for the shapes. They were displayed at the centre of the screen, presenting a size of 124 x 124 mm and subtending a visual angle of approximately 17°. Auditory stimuli were obtained from the website http://www.fromtexttospeech.com/ by converting text files into recordings. A male Italian voice was picked this time in order to pronounce the to-be-heard material. AD patients were presented with two bindings in the test phase, whereas the OA3 group encountered three colour-shape conjunctions per trial. These set sizes are consistent with those used in previous studies (Della Sala et al., 2012; Parra et al., 2009a), indicating that, at this memory load, the performance of both groups would be comparable and avoid ceiling and floor levels. Moreover, the OA2 group processed the same number of items per sequence as the patients, in order to test both experimental and control groups with the same memory load manipulation. Participants were assessed either at the ASL department or at their own home if they were unable to travel. Testing was controlled on a Macintosh iMac with a 13.5-inch screen, placed at approximately 40 cm from the subject, and 'PsychoPy' (version 1.85.1 - Peirce, 2007; 2009) program was used to run the experiment.

Design and procedure

A few adjustments were made to the design used in Experiment 1 and 2 in order to make it more suitable for AD patients. Firstly, conditions were blocked according to the probe type, that is, shape- and colour-probes were not intermixed in the test phase - accounting for the 50% of the test trials each - but they were presented across separate conditions. As a result, the task

included four experimental conditions: 1) Unimodal condition – shape probe; 2) Unimodal condition – colour probe; 3) Crossmodal condition – shape probe; 4) Crossmodal condition – colour probe. Secondly, the four conditions were grouped in two blocks, in order to collect data from all of the four conditions in case any patient could not stand the experimental session for a long time. Therefore, conditions were presented in a counterbalanced order and each accounted for 3 practice trials and 12 test trials per block so that every feature was repeated twice within it. Finally, the time display of each visual feature was set to 1500ms instead of 1000ms in order to give sufficient time for patients to encode the material[3].

Data Analysis

Both frequentist and Bayes Factor data analyses were conducted in R Studio (version 1.1.456; R Core Team, 2013), IBM SPSS Statistics 21, and JASP (version 0.9.2; JASP Team, 2019). Percentage of correct responses as well as errors were analysed by means of mixed ANOVAs.

Results

[3] A pilot study was conducted to ascertain that a longer time display would have not affected the level of performance. Six healthy older adults (Age: M=72.33, SD=4.80; YoE: M=13.67, SD=1.63; 4 men and 2 women) were tested with the 1 sec time display, whereas other six healthy elderly were tested with the 1.5 sec time display (Age: M=72.83, SD=6.31; YoE: M=15.33, SD=1.86; 1 man and 5 women). Results from a 2x2 mixed ANOVA yielded neither a main effect of condition ($F(1,10)= 1.02$, $p= .33$, $\eta^2p = .92$), nor of group ($F(1,10)= .07$, $p= .78$, $\eta^2p = .008$), nor a condition*group interaction ($F(1,10)= .007$, $p= 1$, $\eta^2p <.001$).

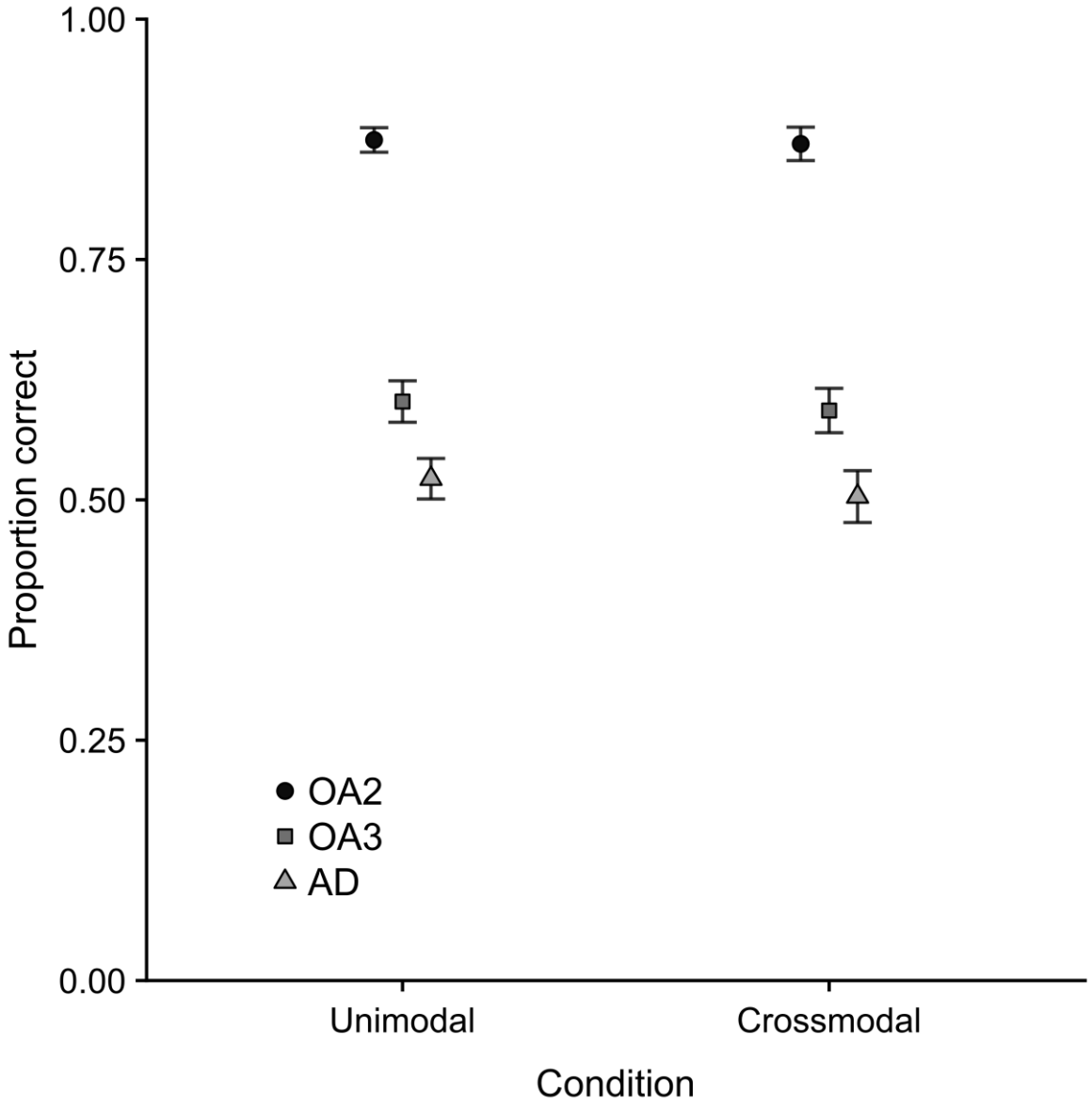

Fig. 9 *- Percentage of correct responses in the Unimodal and Crossmodal conditions for OA2 and OA3 groups, and AD patients.*

Accuracy. A 2x3 mixed ANOVA yielded a significant main effect of group ($F(2,69)= 126.54$, $p< .001$, $\eta^2p= .78$, $BF> 10,000$) as evident from *Figure 9*. Bonferroni pairwise comparisons confirmed that AD (Unimodal: M= .52, SD= .10; Crossmodal: M= .50, SD= .13) were significantly different from both OA2 ($p< .05$) and OA3 ($p< .05$), as well as OA2 (Unimodal: M=

.87, SD= .06; Crossmodal: M= .87, SD= .08) and OA3 (Unimodal: M= .60, SD= .10; Crossmodal: M= .59, SD= .11) showed a significantly different performance ($p < .05$). Neither a main effect of condition ($F(1,69) = .53$, $p = .46$, $\eta^2p = .008$, $BF = .22$) nor a condition*group interaction ($F(2,69) = .08$, $p = .91$, $\eta^2p = .002$, $BF = .13$) were found. The BF analysis endorsed such evidence by revealing that the most likely model included the main effect of group ($BF_{10} > 10{,}000$ relative to the null model including only participant).

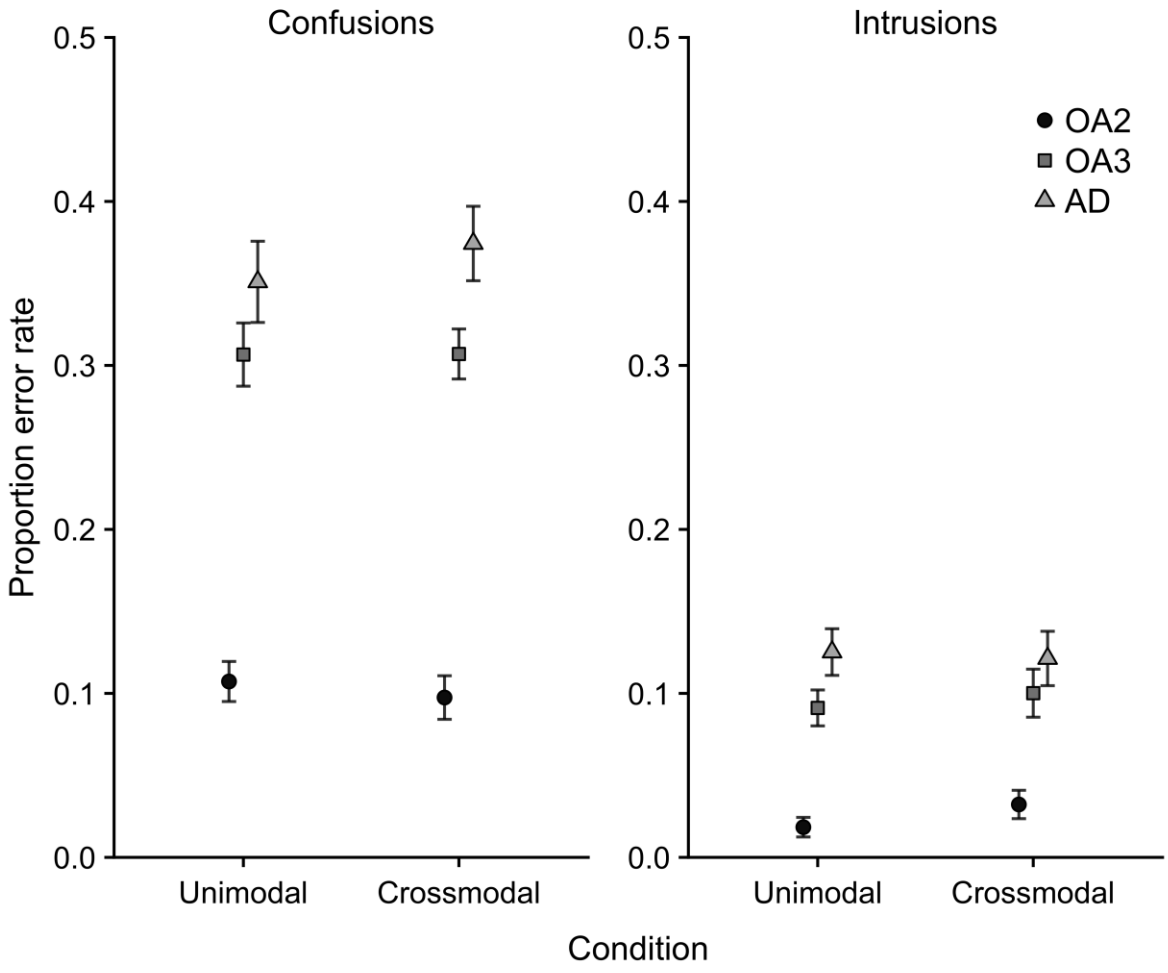

Fig. 10 *– Error rates as a function of within-series confusions and extra-series intrusions for OA2, OA3, and AD patients.*

Error Analysis. Neither a significant effect of condition ($F(1,69)= .16$, $p= .68$, $\eta^2p= .002$, $BF= .15$) nor a condition*group interaction ($F(2,69)= .74$, $p= .47$, $\eta^2p= .02$, $BF= .12$) were shown by the analysis on within-series confusions. The difference among groups was significant ($F(2,69)= 76.33$, $p< .001$, $\eta^2p= .68$, $BF> 10,000$), as displayed in *Figure 10*. The rate for within-series confusions in AD patients (Unimodal: M= .35, SD= .12; Crossmodal: M= .37, SD= .11) was higher compared to both OA2 (Unimodal: M= .10, SD= .05; Crossmodal: M= .09, SD= .06) and OA3 (Unimodal: M= .30, SD= .09; Crossmodal: M= .30, SD= .07). The most likely model, resulted from the BF analysis, included the main effect of group and the condition*group interaction ($BF_{10}> 10,000$ relative to the null model including only participant).

The ANOVA on extra-series intrusions revealed a similar pattern (see also *Figure 10*). Just the main effect of group was significant ($F(2,69)= 26.58$, $p< .001$, $\eta^2p= .43$, $BF> 10,000$), with AD patients' recall memory showing more intrusion of trial-irrelevant features (Unimodal: M= .12, SD= .06; Crossmodal: M= .12, SD= .08) compared to both OA2 (Unimodal: M= .01, SD= .02; Crossmodal: M= .03, SD= .04) and OA3 (Unimodal: M= .09, SD= .05; Crossmodal: M= .10, SD= .07). The main effect of condition ($F(1,69)= .51$, $p= .47$, $\eta^2p= .007$, $BF= .17$) and the two-way interaction ($F(2,69)= .36$, $p= .69$, $\eta^2p= .01$, $BF= .10$) did not account for a significant proportion of variance. The BF analysis suggested that the most likely model included the main effect of group only ($BF_{10}> 10,000$ relative to the null model including only participant).

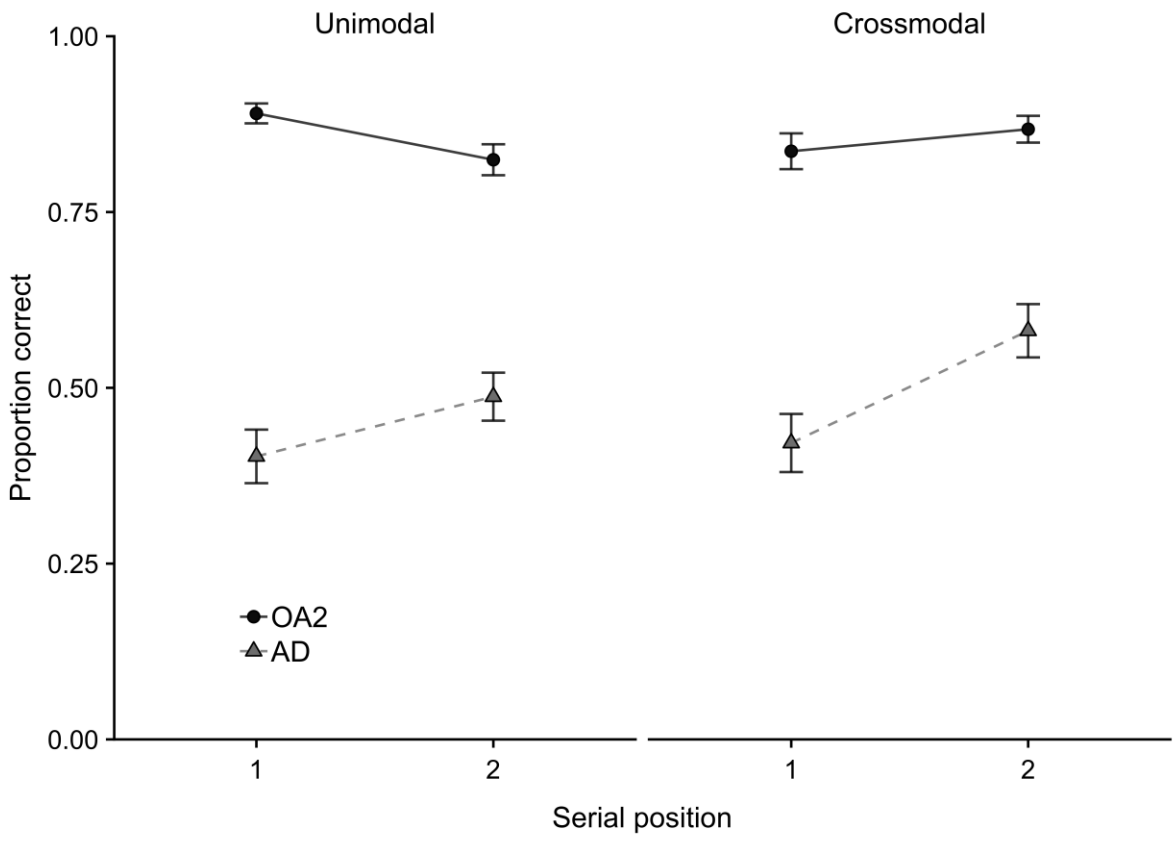

Fig. 11 *– Proportion correct across serial positions for each task condition in OA2 and AD groups.*

Serial Position Analysis. Lastly, the serial position analysis was run for the two groups that processed two bindings only, namely, AD and OA2. A 2x2x2 mixed ANOVA did not present a significant main effect of condition ($F(1,46)= 1.62$, $p= .20$, $\eta^2p= .03$, $BF= .52$), conversely, the serial position factor played a significant role ($F(1,46)= 4.22$, $p= .04$, $\eta^2p= .08$, $BF= 64.18$). The main effect of group was also significant ($F(1,46)= 244.64$, $p< .001$, $\eta^2p= .84$, $BF> 10,000$). The group*SP ($F(1,46)= 7.46$, $p= .009$, $\eta^2p= .14$, $BF= 70.09$) as well as the condition*SP interactions ($F(1,46)= 8.64$, $p= .005$, $\eta^2p= .15$, $BF= 1.27$) reached significance. AD patients and OA2 showed a difference in recalling the items in SP1 ($t(46)= -8.54$, $p< .001$, $d= -2.46$, $BF_{10}> 10,000$) and SP2 ($t(46)= -6.75$, $p< .001$, $d= -1.95$, $BF_{10}= 439,949$) in the Unimodal condition, and in SP1 ($t(46)= -12.00$, $p< .001$, $d= -3.46$, $BF_{10}> 10,000$) and SP2 ($t(46)= -8.29$, $p< .001$, $d= -2.39$, $BF_{10}> 10,000$) in the Crossmodal condition. Furthermore, OA2 were better

at recalling bindings presented as first rather than as second ($t(23)= 3.01$, $p= .006$, $d= .61$, $BF_{10}= 7.29$) in the Unimodal condition, but no difference between the two serial positions was worth of being noticed in the Crossmodal condition ($t(23)= -1.48$, $p= .15$, $d= -.30$, $BF_{10}= .56$). On the contrary, AD patients showed a better memory when items appeared in SP2 compared to SP1 ($t(23)= -2.76$, $p= .01$, $d= -.56$, $BF_{10}= 4.49$) in the Crossmodal condition, but not meaningful difference was registered ($t(23)= -1.64$, $p= .11$, $d= -.33$, $BF_{10}= .69$) in the Unimodal condition. *Figure 11* illustrates all these trends (see also *Table 3* in *Supplementary Material*). No other interactions were meaningful ($p= .13$, $\eta^2p= .04$, $BF= .75$). The BF analysis showed that the most likely model comprised the main effect of group and SP, in addition to the group*SP interaction and the condition*group interaction ($BF_{10}> 10{,}000$ relative to the null model including only participant).

Discussion

Experiment 3 showed that WMB is impaired in patients affected by AD independently of the sensory modality through which the features integration occurs. Indeed, AD patients could recall Unimodal and Crossmodal colour-shape conjunctions to the same extent, suggesting that Unimodal and Crossmodal WMB are not differentially affected by pathological ageing. Also, the error analysis highlighted a greater tendency to recall a feature presented in the study sequence but not matching the test probe in both tasks. This adds to the evidence that the poor performance on WMB is a characteristic of AD that may inform clinical judgements. Finally, the last binding of the series was generally easier to be remembered for both AD patients and controls, except for OA2 in the Unimodal condition where the first conjunction of the series was the best retained. In summary, Experiment 3 endorsed the conclusion that WMB is a reliable cognitive marker for AD (Cecchini et al., 2017; Della Sala et al., 2012; Parra et al., 2009a; Parra et al., 2010b), regardless of modality of feature presentation.

General Discussion

The three experiments discussed in the present study examined whether Unimodal and Crossmodal working memory binding (WMB) are similarly affected by healthy or pathological ageing. Experiment 1 and 2 addressed this question in a healthy ageing population. No greater age-related decline for Unimodal WMB capacities, compared to single features memory, has been reported across the lifespan whenever participants were tested with a recognition task (Brockmole et al., 2008; Parra et al., 2009a). Consistently, results from Experiment 1 revealed that performance in Crossmodal and Unimodal conditions did not differ in either of the two age groups when using a cued-recall paradigm. This finding was confirmed by the outcome of Experiment 2, whereby participants were engaged in a concurrent interference task (i.e., articulatory suppression) while performing the WMB test. Although articulatory suppression undermined global performance leading to a decrement in accuracy, younger adults outperformed the healthy older participants solely in the Unimodal condition. Age-related slowness at processing information is more pronounced in the visuospatial compared to the verbal domain (Hale & Myerson, 1996; Jenkins et al., 2000; Lawrence, Myerson, & Hale, 1999; Lima, Hale, & Myerson, 1991). It is possible that older participants were less accurate at encoding the shapes of the present paradigm, which were displayed quite briefly, and thus tried to rely more upon what they heard because it was easier to process. Indeed, whenever auditory spoken material is processed, it enters the phonological store directly in the same order as it has been encoded (Baddeley, 2007); on the other hand, visual items must be phonologically coded beforehand. Perhaps, this increased the demand on older adults' capacity, especially when articulatory suppression interfered with such procedure. Similarly, a greater age-related deficit in visuospatial than verbal WM has often been reported (e.g., Jenkins et al., 2000; Johnson et al., 2010), and, it may be worth noticing that results from Experiment 2 show a higher accuracy

for healthy older participants in the Crossmodal condition compared to the Unimodal condition (albeit the within-group performance did not differ significantly). Thus, age-related differences in WMB performance may be more pronounced in purely visual tasks, and reduced when the task has a verbal component (Crossmodal WMB). One caveat to note is that while the cross-experiment analysis produced a condition x group interaction, with an age-related difference in Unimodal but not Crossmodal WMB, articulatory suppression did not interact with other factors. Thus, follow-up work is needed to directly explore how verbal recoding and rehearsal might influence performance across age groups and WM binding conditions. An additional possible limitation of the study is the recruitment of undergraduate university students as the younger participant group, as this may not be representative of the entire population. However, the younger group did not report more years of education, relative to the older group, in either Experiment 1 or 2. In addition, it is not clear how any advantage for the younger groups of participants in the current experiments (apart from their relative age) might manifest in the particular patterns of outcomes observed across the different WM binding conditions.

Subsidiary analyses derived from both Experiment 1 and 2 shed light on other important aspects of the performance. The error analysis indicated a common bias for recalling a feature presented in the study sequence but not matching the test probe. This reflected the tendency of forgetting the exact targeted combination as the result of a WMB error (e.g. Hu et al., 2014; Ueno, Mate, Allen, Hitch, & Baddeley, 2011). Moreover, the serial position analysis yielded a general trend to recall the last item of the series better than earlier items (e.g. Allen et al., 2006; 2014). As emerged from the debriefing session, most participants used the same strategy to cope with their limited WM capacity: they reported to focus on a sub-set of the visual array, precisely on the first two items of the series, since the trace of the third one was more vivid in their memory. This is in line with recent findings (e.g. Atkinson, Baddeley, & Allen, 2018; Hu,

Allen, Baddeley, & Hitch, 2016), suggesting that participants can strategically prioritise a subset of items in order to support performance. In conclusion, both Experiment 1 and 2 led to the evidence that the ability to form and temporarily store Crossmodally bound representations does not decline with ageing, and that age does not have any differential effect on Crossmodal relative to Unimodal WMB.

The second question that we were interested in addressing concerned Crossmodal WMB performance in AD. Experiment 3 revealed that AD patients performed significantly less accurately than the healthy control group, even when the latter was challenged with a more demanding task (i.e., increased set size). This proved equally true for both the Crossmodal and the Unimodal WMB task. Of note, we also calculated participants' WM capacity based on Cowan's formula (Chen & Cowan, 2013; Cowan, 2001) adapted to the current paradigm (see Atkinson et al., 2018 for a description of the calculation). Both groups of older controls could retain, on average, approximately 1.5 items regardless of the memory set size or the binding condition. AD patients could maintain approximately .80 to .85 item (i.e., less than 1 item, on average) across the same conditions. The error analysis for this study also verified that AD patients showed an increased tendency to recall a feature that had been displayed in the study array but did not match the cue afterwards. These findings are consistent with those from previous neuropsychological studies demonstrating that the poor attainment shown by AD patients in WMB tasks is the result of a deficit related to the binding mechanism.

The temporary retention of visual colour-shape conjunctions (Unimodal conjunctive WMB) activates a cortical network involving the ventral stream (including the perirhinal cortex), the fusiform gyrus, the left inferior temporal lobe, the left superior and inferior parietal cortex, and the left dorsal premotor cortex (Parra et al., 2014). It has been claimed that some of these regions (e.g., higher visual areas) reflected the type of stimuli used in the study (i.e., visual colour-shape conjunctions), with parietal regions engaged to provide the 'glue' that allowed the

features to be maintained as bound during online processing (Parra et al., 2014; Shafritz, Gore, & Marois, 2002; Song & Jiang, 2006; Xu, 2007; Xu & Chun, 2006).

Importantly, the perirhinal cortex has been acknowledged as the neural locus wherein both Crossmodal integration and complex visual processes occur (Della Sala et al., 2012; Parra et al., 2014; Taylor et al., 2006). In AD, abnormal neuropathological changes commence in the medial portion of the perirhinal cortex, sequentially spreading across parahippocampal cortices, to finally reach the whole medial temporal lobe and ultimately the entire brain (Didic et al., 2011). As a consequence, binding deficits are among the first signs of cognitive decline in AD, as revealed in studies with asymptomatic carriers of a gene mutation inevitably leading to AD (Parra et al., 2010b; 2017; 2015). Moreover, the fact that perirhinal degeneration is a hallmark of AD would justify the reliability of WMB tasks to discriminate among AD and healthy older adults (Parra et al., 2009a), and AD and other types of dementia (i.e., Fronto-Temporal Dementia, Parkinson's Disease with Dementia, Vascular Dementia, Dementia with Lewy Bodies - Cecchini et al., 2017; Della Sala et al., 2012). Although the current study was not designed to address the neural correlates of Crossmodal WMB, we may speculate that the WMB deficits observed in AD are ascribed to the integrative functioning of the perirhinal cortex. Indeed, our results suggest that bound representations are formed at encoding and maintained in WM as single units, and that the modalities through which sensory information is bound are secondary compared to the severe impairments encountered by AD patients in the binding process.

In addition, the involvement of a wide neural circuit hints at the evidence that WMB functions rely upon effective connectivity among brain areas (Logie, 2011; O'Reilly, Busby, & Soto, 2003; Koenig, Studer, Hubl, Melie, & Strik, 2005). It has been postulated that AD leads to a disconnection syndrome (Bozzali & Cherubini, 2011; Delbeuck, Van der Linden, & Collette, 2003; Chua, Wen, Slavin, & Sachdev, 2008; Gili, Cercignani, Serra, Perri, Giove,

Maraviglia, Caltagirone, & Bozzali, 2011; Stahl, Dietrich, Teipel, Hampel, Reiser, & Schoenberg, 2007), and it has been posited that WMB deficits may be underpinned by it (Parra et al., 2017; 2015).

To conclude, we maintain that the disruption of connections among cortical areas, originated in the perirhinal cortex, is a hallmark of both preclinical and clinical AD and serves temporary binding functions despite any specific to-be-bound material. The current study is consistent with the conclusion that WMB deficits are sensitive and specific to AD independently of the modality through which information is integrated.

Working Memory Binding and the Episodic Buffer

The current study aimed to investigate age- and pathology-related differences in the binding and temporary storage of features derived from either the same (i.e., visual) or diverse sensory modalities (i.e., visual and auditory) at the same time. Overall, the study of WMB mechanism was prompted by the concept of the Episodic Buffer (EB) proposed by Baddeley (2000) as the fourth component of the Multicomponent Model of WM (Baddeley & Hitch, 1974).

The EB has been conceived as a limited capacity storage system whereby separate visuospatial and verbal information streaming from the visuospatial sketchpad and the phonological loop, respectively, is integrated. Originally, the EB was theorised to depend upon the Central Executive (CE), a control system needed to supply attention whenever WM tasks are undertaken. Since Baddeley's amendments to the model (2000), a wide corpus of research has examined the relationship between these two systems. The rationale was: if the CE controls access to and from the EB, then an attentionally demanding concurrent task should negatively affect participants' performance in binding WM information.

Results have confuted such expectations as it was shown that no greater attention is required to bind surface features (i.e., colours and shapes) than to process them separately (Allen et al., 2006; Allen, Hitch, Mate, & Baddeley, 2012), and this holds true for words bound into sentences compared to individual words as well (Allen & Baddeley, 2008; Baddeley, Hitch, & Allen, 2009). Also, concurrent demanding tasks have been observed to not disrupt participants' performance when features are presented as spatially and temporally separated and required to be retained as bound afterwards (Karlsen, Allen, Baddeley, & Hitch, 2010). Finally, as discussed earlier, Allen and colleagues (2009) have broadened these findings by suggesting that individuals' capacity to integrate features delivered across diverse modalities (Crossmodal WMB) does not rely on major attentional resources compared to Unimodally bound material and single features.

Taken together, it has been demonstrated so far that WMB can occur across locations, across time, and across modalities without employing a greater pool of attentional resources, and that the EB allows the temporary maintenance of bound information and potentially facilitates its long-term storage. The present studies add to this evidence for older and clinical populations.

References

Alain, C., & Woods, D.L. (1999). Age-related changes in processing auditory stimuli during visual attention: evidence for deficits in inhibitory control and sensory memory. *Psychology and Aging*, 14, 507–519. doi:http://dx.doi.org/10.1037/0882-7974.14.3.507

Allen, R.J., & Baddeley, A.D. (2008). Working memory and sentence recall. In: Thorn, A., & Page, M. *Interactions between Short-Term and Long-Term Memory in the Verbal Domain*. Taylor & Francis Group, 4.

Allen, R.J., Baddeley, A.D., & Hitch, G.J. (2006). Is the binding of visual features in working memory resource-demanding?. *Journal of Experimental Psychology: General,* 135(2), 298-313. doi:http://dx.doi.org/10.1037/0096-3445.135.2.298

Allen, R.J., Hitch, G.J., Mate, J., & Baddeley, A.D. (2012). Feature binding and attention in working memory: A resolution of previous contradictory findings. *The Quarterly Journal of Experimental Psychology*, 65(12), 2369-2383. doi:https://doi.org/10.1080/17470218.2012.687384

Allen, R.J., Baddeley, A.D., & Hitch, G.J. (2014). Evidence for two attentional components in visual working memory. *Journal of Experimental Psychology: Learning, Memory and Cognition,* 40(6), 1499-1509. doi:http://dx.doi.org/10.1037/xlm0000002

Allen, R.J., Hitch, G.J., & Baddeley, A.D. (2009). Cross-modal binding and working memory. *Visual Cognition*, 17(1-2), 83-102. doi:10.1080/13506280802281386

Arenberg, D. (1973). Cognition and aging: Verbal learning, memory and problem solving. In C. Eisdorfer & M. P. Lawton (Eds.), *The psychology of adult development and aging* (pp. 74-97). Washington, DC: American Psychological Association.

Atkinson, A.L., Baddeley, A.D., & Allen, R.J. (2018). Remember some or remember all? Ageing and strategy effects in visual working memory. *The Quarterly Journal of Experimental Psychology*, 71(7), 1561-1573. doi:10.1080/17470218.2017.1341537

Baddeley, A. (2000). The episodic buffer: A new component of working memory?. *Trends in Cognitive Sciences*, 4(11), 417-423. doi:https://doi.org/10.1016/S1364-6613(00)01538-2

Baddeley, A. (2007). Working memory, thought, and action. *Oxford Psychology Series*, 45. New York, NY, US: Oxford University Press. doi:http://dx.doi.org/10.1093/acprof:oso/9780198528012.001.0001

Baddeley, A.D., & Hitch, G. (1974). Working memory. *Psychology of Learning and Motivation*, 8, 47-89. doi:https://doi.org/10.1016/S0079-7421(08)60452-1

Baddeley, A.D., Hitch, G.J., & Allen, R.J. (2009). Working memory and binding in sentence recall. *Journal of Memory and Language*, 61(3), 438-456. doi:https://doi.org/10.1016/j.jml.2009.05.004

Blackwell, A.D., Sahakian, B.J., Vesey, R., Semple, J.M., Robbins, T.W., & Hodges, J.R. (2004). Detecting dementia: novel neuropsychological markers of preclinical Alzheimer's disease. *Dementia and Geriatric Cognitive Disorders,* 17(1-2), 42–48. doi:https://doi.org/10.1159/000074081

Borkowski, J.G., Benton, A.L., & Spreen, O. (1967). Word fluency and brain damage. *Neuropsychologia*, 5(2), 135–140. doi:http://dx.doi.org/10.1016/0028-3932(67)90015-2

Bozzali, M., & Cherubini, A. (2011). A diffusion tensor MRI to investigate dementias: A brief review. *Magnetic Resonance Imaging*, 25(6), 969-977. doi:10.1016/j.mri.2007.03.017

Brink, T.L., Yesavage, J.A., Lum, O., Heersema, P., Adey, M.B., & Rose, T.L. (1982). Screening tests for geriatric depression. *Clinical Gerontologist,* 1*,* 37-44. doi:https://doi.org/10.1300/J018v01n01_06

Brockmole, J.R., & Logie, R.H. (2013). Age-related change in visual working memory: A study of 55,753 participants aged 8 to 75. *Frontiers in Perception Science*, 4, 12. doi:10.3389/fpsyg.2013.00012

Brockmole, J.R., Parra, M.A., Della Sala, S., & Logie, R.H. (2008). Do binding deficits account for age-related decline in visual working memory?. *Psychonomic Bulletin & Review*, 15(3), 543-547. doi:10.3758/PBR.15.3.543

Brooks, C.J., Chan, Y.M., Anderson, A.J., & McKendrick, A.M. (2018). Audiovisual temporal perception in aging: The role of multisensory integration and age-related sensory loss. *Frontiers in Human Neuroscience*, 12, 192. doi:10.3389/fnhum.2018.00192

Brown, L.A., & Brockmole, J.R. (2010). The role of attention in binding visual features in working memory: Evidence from cognitive ageing. *Quarterly Journal of Experimental Psychology*, 63(10), 2067-2079. https://doi-org.ezproxy.is.ed.ac.uk/10.1080/17470211003721675

Brown, L.A., Niven, E.H., Logie, R.H., Rhodes, S., & Allen, R.J. (2017). Visual feature binding in younger and older adults: encoding and suffix interference effects. *Memory*, 25(2), 261-275. doi:10.1080/09658211.2016.1156705

Brown, L.A., & Wesley, R.W. (2013). Visual working memory is enhanced by mixed strategy use and semantic coding. *Journal of Cognitive Psychology*, 25(3), 328-338. doi: 10.1080/20445911.2013.773004

Bunce, D., & Macready, A. (2005). Processing speed, executive function, and age differences in remembering and knowing. *The Quarterly Journal of Experimental Psychology A: Human Experimental Psychology*, 58(1), 155–168. doi:10.1080/02724980443000197

Burke, D.M., & Light, L.L. (1981). Memory and aging: The role of retrieval processes. *Psychological Bulletin,* 90(3)*,* 513-546. doi:http://dx.doi.org/10.1037/0033-2909.90.3.513

Cecchini, M.A., Yassuda, M.S., Bahia, V.S., de Souza, L.C., Guimarães, H.C., Caramelli, P., Carthery-Goulart, M.T., Patrocinio, F., Foss, M.P., Tumas, V., Lima-Silva, T.B., Brucki, S.M.D., Nitrini, R., Della Sala, S., & Parra, M.A. (2017). Recalling feature binding differentiates Alzheimer's disease from frontotemporal dementia. *Journal of Neurology*, 264(10), 2162-2169. doi:10.1007/s00415-017-8614-9

Chen, Z., & Cowan, N. (2013). Working memory inefficiency: Minimal information is utilized in visual recognition tasks. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 39(5), 1449–1462. doi:10.1037/a0031790

Chua, T.C., Wen, W., Slavin, M.J., & Sachdev, P.S. (2008). Diffusion tensor imaging in mild cognitive impairment and Alzheimer's disease: A review. *Current Opinion in Neurology*, 21(1), 83-92. doi:10.1097/WCO.0b013e3282f4594b

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences*, 24(1), 87–114. doi:10.1017/S0140525X01003922

Craik, F.I.M. (1977). Age differences in human memory. In J. E. Birren & K. W. Schaie (Eds.), *Handbook of the psychology of aging* (pp. 384- 420). New York: Van Nostrand Reinhold.

Craik, F.I.M. (1983). On the transfer of information from temporary to permanent memory. *Philosophical Transactions of the Royal Society of London, Series B, Biological Sciences,* 302(1110), 341-359. doi:https://doi.org/10.1098/rstb.1983.0059

Craik, F.I.M., & McDowd, J.M. (1987). Age differences in recall and recognition. *Journal of Experimental Psychology*, 13(3), 474-479. doi:00004786-198707000-00013

Delbeuck, X, Van der Linden, M., & Collette, F. (2003). Alzheimer's disease as a disconnection syndrome?. *Neuropsychology Review*, 13(2), 79-92. doi:10.1023/A:1023832305702

Della Sala, S., Parra, M.A., Fabi, K., Luzzi, S., & Abrahams, S. (2012). Short-term memory binding is impaired in AD but not in non-AD dementias. *Neuropsychologia*, 50(5), 833-840. doi:10.1016/j.neuropsychologia.2012.01.018

Didic, M., Barbeau, E.J., Felician, O., Tramoni, E., Guedj, E., Poncet, M., & Ceccaldi, M. (2011). Which memory system is impaired first in Alzheimer's disease?. *Journal of Alzheimer's Disease*, 27(1), 11-22. doi:10.3233/JAD-2011-110557

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: Tests for correlation and regression analyses. *Behavior Research Methods*, 41(4), 1149-1160. doi:10.3758/BRM.41.4.1149

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39(2), 175-191.

Folstein, M.F., Folstein, S.E., & McHugh, P.R. (1975). "Mini-Mental State": A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, 12(3), 189-198. doi:10.1016/0022-3956(75)90026-6

Fowler, K.S., Saling, M.M., Conway, E.L., Semple, J.M., & Louis, W.J. (2002). Paired associate performance in the early detection of DAT. *Journal of the International Neuropsychological Society*, 8(1), 58–71. doi:https://doiorg.ezproxy.is.ed.ac.uk/10.1017/S1355617701020069

Frasson, P., Ghiretti, R., Catricalà, E., Pomati, S., Marcone, A., Parisi, L., Rossini, P.M., Cappa, S.F., Mariani, C., Vanacore, N., & Clerici, F. (2011). Free and Cued Selective Reminding Test: an Italian normative study. *Neurological Sciences*, 32(6), 1057-1062. doi:10.1007/s10072-011-0607-3

Gajewski, D.A., & Brockmole, J.R. (2006). Feature bindings endure without attention: Evidence from an explicit recall task. *Psychonomic Bulletin & Review*, 13(4), 581-587.

Gao, Z., Wu, F., Qiu, F., He, K., Yang, Y., & Shen, M. (2017). Bindings in working memory: The role of object-based attention. *Attention, Perception, & Psychophysics*, 79(2), 533-552. doi:10.3758/s13414-016-1227-z

Gili, T., Cercignani, M., Serra, L., Perri, R., Giove, F., Maraviglia, B., Caltagirone, C., & Bozzali, M. (2011). Regional brain atrophy and functional disconnection across Alzheimer's disease evolution. *Journal of Neurology, Neurosurgery, and Psychiatry*, 82(1), 58–66. doi:10.1136/jnnp.2009.199935

Grober, E., & Buschke, H. (1987). Genuine memory deficits in dementia. *Developmental Neuropsychology*, 3(1), 13-36. doi:https://doi.org/10.1080/87565648709540361

Guerreiro, M.J.S., Anguera, J.A., Mishra, J., Van Gerven, P.W.M., & Gazzaley, A. (2014). Age-equivalent top-down modulation during cross-modal selective attention. *Journal of Cognitive Neuroscience*, 26(12), 2827-2839. doi:10.1162/jocn_a_00685

Hale, S., & Myerson, J. (1996). Experimental evidence for differential slowing in the lexical and nonlexical domains. *Aging, Neuropsychology, and Cognition,* 3(2), 154-165.

Hasher, L., & Zacks, R.T. (1979). Automatic and effortful processes in memory. *Journal of Experimental Psychology: General,* 108(3), 356- 388. doi:http://dx.doi.org/10.1037/0096-3445.108.3.356

Hu, Y., Allen, R.J., Baddeley, A.D., & Hitch, G.J. (2016). Executive control of stimulus-driven and goal-directed attention in visual working memory. *Attention, Perception, & psychophysics*, 78(8), 2164-2175. doi:10.3758/s13414-016-1106-7

Hu, Y., Hitch, G.J., Baddeley, A.D., Zhang, M., & Allen, R.J. (2014). Executive and perceptual attention play different roles in visual working memory: Evidence from suffix and strategy effects. *Journal of Experimental Psychology: Human Perception and Performance*, 40(4), 1665–1678. doi:10.1037/a0037163

IBM Corp. Released 2012. IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY: IBM Corp.

Isella, V., Molteni, F., Mapelli, C., & Ferrarese, C. (2015). Short term memory for single surface features and bindings in ageing: A replication study. *Brain and Cognition*, 96, 38–42. doi:10.1016/j.bandc.2015.02.002

JASP Team (2019). JASP (version 0.9.2). Windows 10.

Jenkins, L., Myerson, J., Joerding, J.A., & Hale, S. (2000). Converging evidence that visuospatial cognition is more age-sensitive than verbal cognition. *Psychology and Ageing*, 15(1), 157-175. doi:I0.1037//0882-7974.15.1.157

Johnson, W., Logie, R.H., & Brockmole, J.R. (2010). Working memory tasks differ in factor structure across age cohorts: Implications for dedifferentiation. *Intelligence*, 38(5), 513–528. doi:10.1016/j.intell.2010.06.005

Karlsen, P.J., Allen, R.J., Baddeley, A.D., & Hitch, G.J. (2010). Binding across space and time in visual working memory. *Memory & Cognition*, 38(3), 292-303. doi:10.3758/MC.38.3.292

Katz, S., Ford, A.B., Moskowitz, R.W., Jackson, B.A., & Jaffe, M.W. (1963). Studies of illness in the aged. The index of ADL: A standardised measure of biological and psychosocial function. *Journal of the American Medical Association*, 185(12), 914-919. doi:10.1001/jama.1963.03060120024016

Koenig, T., Studer, D., Hubl, D., Melie, L., & Strik, W.K. (2005). Brain connectivity at different time-scales measured with EEG. *Philosophical Transactions of the Royal Society, Series B, Biological Sciences*, 360(1457), 1015–1023. doi:https://doi.org/10.1098/rstb.2005.1649

Laurienti, P.J., Burdette, J.H., Maldjian, J.A., & Wallace, M.T. (2006). Enhanced multisensory integration in older adults. *Neurobiology of Aging*, 27, 1155– 1163.doi:10.1016/j.neurobiolaging.2005.05.024

Lawrence, B., Myerson, J., & Hale, S. (1999). Differential decline of verbal and visuospatial processing speed across the adult life span. *Aging, Neuropsychology, & Cognition*, 5(2), 129-146. doi:https://doi.org/10.1076/anec.5.2.129.600

Lima, S. D., Hale, S., & Myerson, J. (1991). How general is general slowing? Evidence from the lexical domain. *Psychology and Aging,* 6(3)*,* 416-425. doi:10.1037/0882-7974.6.3.416

Logie, R.H. (2011). The functional organization and capacity limits of working memory. *Current Directions in Psychological Science*, 20(4), 240–245. doi:http://dx.doi.org/10.1177/0963721411415340

Luck, S.J., & Vogel, E.K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, 390(6657), 279-281. doi:10.1038/36846

McKhann, G., Drachman, D., Folstein, M., Katzman, R., Price, D., & Stadlan, E.M. (1984). Clinical diagnosis of Alzheimer's Disease: Report of the NINCDS-ADRDA Work Group* under the auspices of Department of Health and Human Services Task Force on Alzheimer's Disease. *Neurology*, 34(7), 939-944. doi:10.1212/WNL.34.7.939

McKhann, G.M., Knopman, D.S., Chertkow, H., Hyman, B.T., Jack,Jr., C.R., Kawas, Klunk, W.E., Koroshetz, W.J., Manly, J.J., Mayeux, R., Mohs, R.C., Morris, J.C., Rossor, M.N., Scheltens, P., Carrillo, M.C., Thies, B., Weintraub, S., & Phelps, C.H. (2011). The diagnosis of dementia due to Alzheimer's Disease: Recommendations from the National Institute on Aging-Alzheimer's Association workgroups on diagnostic guidelines for Alzheimer's Disease. *Alzheimer's & Dementia*, 7(3), 263-269. doi:10.1016/j.jalz.2011.03.005

Mioshi, E., Dawson, K., Mitchell, J., Arnold, R., & Hodges, J.R. (2006). The Addrenbrooke's Cognitive Examination Revised (ACE-R): A brief cognitive test battery for dementia screening. *International Journal of Geriatric Psychiatry*, 21(11), 1078-1085. doi:10.1002/gps.1610

Mozolic, J.L., Hugenschmidt, C.E., Peiffer, A.M., & Laurienti, P.J. (2012). Multisensory integration and aging. In M.M., Murray and M.T. Wallace (Eds.), *The neural bases of multisensory processes*. Boca Raton (FL): CRC Press/Taylor & Francis.

Murray, E.A., & Bussey, T.J. (1999). Perceptual-mnemonic functions of the perirhinal cortex. *Trends in Cognitive Sciences*, 3(4), 142-151. doi:https://doi.org/10.1016/S1364-6613(99)01303-0

Murray, E.A. & Richmond, B.J. (2001). Role of perirhinal cortex in object perception, memory and associations. *Current Opinion in Neurobiology*, 11(2), 188-193. doi:10.1016/s0959-4388(00)00195-1

O'Connell, H., Coen, R., Kidd, N., Warsi, M., Chin, A.V., & Lawlor, B.A. (2004). Early detection of Alzheimer's disease (AD) using the CANTAB paired Associates Learning Test. *International Journal of Geriatric Psychiatry*, 19(12), 1207–1208. doi:https://doi.org/10.1002/gps.1180

O'Reilly, R.C., Busby, R.S., & Soto, R. (2003). Three forms of binding and their neural substrates: alternatives to temporal synchrony. In: Cleeremans A, editor. *The unity of consciousness: Binding, Integration, and Dissociation*. Oxford: Oxford University Press, 168–192.

Orsini, A., Trojano, L., & Chiacchio, L. (1988). Immediate memory spans in dementia. *Perceptual and Motor Skills*, 67(1), 267-272. doi:https://doi.org/10.2466/pms.1988.67.1.267

Parra, M.A., Abrahams, S., Fabi, K., Logie, R., Luzzi, S., & Della Sala, S. (2009a). Short-term memory binding deficits in Alzheimer's disease. *Brain*, 132(4), 1057-1066. doi:10.1093/brain/awp036

Parra, M.A., Abrahams, S., Logie, R.H., & Della Sala, S. (2009b). Age and binding within-dimension features in visual short-term memory. *Neuroscience Letters*, 449(1), 1-5. doi:https://doi.org/10.1016/j.neulet.2008.10.069

Parra, M.A., Abrahams, S., Logie, R.H., & Della Sala, S. (2010a). Visual short-term memory binding in Alzheimer's disease and depression. *Journal of Neurology*, 257(7), 1160-1169. doi:10.1007/s00415-010-5484-9

Parra, M.A., Abrahams, S., Logie, R.H., Mendez, L.G., Lopera, F., & Della Sala, S. (2010b). Visual short-term memory binding deficits in familial Alzheimer's disease. *Brain*, 133(9), 2702-2713. doi:10.1093/brain/awq148

Parra, M.A., Della Sala, S., Logie, R.H., & Morcom, A. (2014). Neural correlates of shape-color binding in visual working memory. *Neuropsychologia*, 52, 27-36. doi:10.1093/brain/awq148

Parra, M.A., Mikulan, E., Trujillo, N., Della Sala, S., Lopera, F., Manes, F., Starr, J., & Ibáñez, A. (2017). Brain information sharing during visual short-term memory binding yields a memory biomarker for familial Alzheimer's disease. *Current Alzheimer Research*, 14(12), 1335-1347. doi:10.2174/1567205014666170614163316

Parra, M.A., Saarimäki, H., Bastin, M.E., Londoño, A.C., Pettit, L., Lopera, F., Della Sala, S., & Abrahams, S. (2015). Memory binding and white matter integrity in familial Alzheimer's disease. *Brain*, 138(5), 1355-1369. doi:10.1093/brain/awv048

Peiffer, A.M., Mozolic, J.L., Hugenschmidt, C.E., & Laurienti, P.J. (2007). Age-related multisensory enhancement in a simple audiovisual detection task. *NeuroReport*, 18(10), 1077–1081. doi:10.1097/WNR.0b013e3281e72ae7

Peirce, J.W. (2007). PsychoPy – Psychophysics software in Python. *Journal of Neuroscience Methods*, 162(1-2), 8-13.

Peirce, J.W. (2009). Generating stimuli for neuroscience using PsychoPy. *Frontiers in Neuroinformatics*, 2-10. doi:10.3389/neuro.11.010.2008

R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Rhodes, S., Parra, M.A., Cowan, N., & Logie, R.H. (2017). Healthy aging and visual working memory: The effect of mixing feature and conjunction changes. *Psychology and Aging*, 32(4), 354-366. doi:http://dx.doi.org/10.1037/pag0000152

Robinson, C.W., & Sloutsky, V.M. (2010). Development of cross-modal processing. *WIREs Cognitive Science*, 1, 135-141. doi:10.1002/wcs.12

Rouder, J.N., Morey, R.D., Speckman, P.L., & Province, J.M. (2012). Default Bayes factors

for ANOVA designs. *Journal of Mathematical Psychology*, 56, 356-374. doi:10.1016/j.jmp.2012.08.001

Schonfield, D., & Robertson, B.A. (1966). Memory storage and aging. *Canadian Journal of Psychology,* 20(2)*,* 228-236. doi:http://dx.doi.org/10.1037/h0082941

Shafritz, K.M., Gore, J.C., & Marois, R. (2002). The role of the parietal cortex in visual feature binding. *Proceedings of the National Academy of Sciences of the United States of America*, 99(16), 10917–10922. doi:10.1073/pnas.152694799

Siciliano, M., Raimo, S., Tufano, D., Basile, G., Grossi, D., Santangelo, F., Trojano, L., & Santangelo, G. (2016). The Addenbrooke's Cognitive Examination Revised (ACE-R) and its sub-scores: Normative values in an Italian population sample. *Neurological Sciences*, 37(3), 385-392. doi:10.1007/s10072-015-2410-z

Song, J. H., & Jiang, Y. (2006). Visual working memory for simple and complex features: An fMRI study. *Neuroimage*, 30(3), 963–972. doi:http://dx.doi.org/10.1016/j.neuroimage.2005.10.006

Spinnler, H., & Tognoni, G. (1987). Standardizzazione e taratura italiana di test neuropsicologici. *Italian Journal of Neurological Sciences*, 8(6), 44–46.

Stahl, R., Dietrich, O., Teipel, S.J., Hampel, H., Reiser, M.F., & Schoenberg, S.O. (2007). White matter damage in Alzheimer disease and mild cognitive impairment: Assessment with diffusion-tensor MR imaging and parallel imaging techniques. *Radiology*, 243(2), 483-492. doi:https://doi.org/10.1148/radiol.2432051714

Suzuki, W.L., & Amaral, D.G. (1994). Perirhinal and parahippocampal cortices of the macaque monkey: Cortical afferents. *Journal of Comparative Neurology*, 350(4), 497-533. doi:https://doi.org/10.1002/cne.903500402

Swainson, R., Hodges, J.R., Galton, C.J., Semple, J., Michael, A., Dunn, B.D., Iddon, J.L., Robbins, T.W., & Sahakian, B.J. (2001). Early detection and differential diagnosis of Alzheimer's disease and depression with neuropsychological tasks. *Dementia and Geriatric Cognitive Disorders*, 12(4), 265–280. doi:10.1159/000051269

Talsma, D., & Woldorff, M.G. (2005). Selective attention and multisensory integration: multiple phases of effects on the evoked brain activity. *Journal of Cognitive Neuroscience*, 17, 1098–1114. doi:https://doi-org.ezproxy.is.ed.ac.uk/10.1162/0898929054475172

Taylor, K.I., Moss, H.E., Stamatakis, E.A., & Tyler, L.K. (2006). Binding crossmodal object features in perirhinal cortex. *PNAS*, 103(21), 8239-8244. doi:10.1073/pnas.0509704103

Tyler, L.K., Stamatakis, E.A., Bright, P., Acres, K., Abdallah, S., Rodd, J.M., & Moss, H.E. (2004). Processing objects at different levels of specificity. *Journal of Cognitive Neuroscience*, 16(3), 351-362. doi:10.1162/089892904322926692

Ueno, T., Mate, J., Allen, R.J., Hitch, G.J., & Baddeley, A.D. (2011). What goes through the gate? Exploring interference with visual feature binding. *Neuropsychologia*, 49(6), 1597-1604. doi:10.1016/j.neuropsychologia.2010.11.030.

Xu, Y. (2007). The role of the superior intraparietal sulcus in supporting visual short-term memory for multifeature objects. *Journal of Neuroscience*, 27(43), 11676–11686. doi:https://doi.org/10.1523/JNEUROSCI.3545-07.2007

Xu, Y., & Chun, M. M. (2006). Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature*, 440(7080), 91–95. doi:10.1038/nature04262

Zimmer, H. D., Mecklinger, A., & Lindenberger, U. (2006). Leves of binding: types, mechanisms, and functions of binding. In H. D. Zimmer, A. Mecklinger, & U. Lindenberger (Eds.), *Handbook of binding and memory, perspective from cognitive neuroscience* (pp. 3-25). New York: Oxford University Press.

Supplementary material

Written instructions as displayed at the beginning of each experimental condition are reported. In the Unimodal condition, participants were told "*You are going to see a sequence of three coloured shapes on the screen. After a brief delay interval, either one coloured blob or one blank shape will be presented. If you see a coloured blob, try to recall out loud the shape it was presented in. If you see a blank shape, try to recall out loud the colour it was*". In the Crossmodal condition, they read "*You are going to see a sequence of three blank shapes on the screen while listening to colour names at the same time. After a brief delay interval, either one coloured blob or one blank shape will be presented. If you see a coloured blob, try to recall out loud the shape it was associated with. If you see a blank shape, try to recall out loud the matching colour*".

Table 1 *– Mean accuracy and SD as a function of Serial Position (SP) for both age groups in Experiment 1.*

	Younger (N = 26)				**Older** (N = 26)			
	Unimodal		**Crossmodal**		**Unimodal**		**Crossmodal**	
	M	SD	M	SD	M	SD	M	SD
SP 1	.79	.16	.73	.19	.66	.17	.62	.23
SP 2	.73	.22	.69	.20	.61	.19	.63	.20
SP 3	.83	.13	.81	.20	.79	.12	.77	.13

Table 2 *– Mean accuracy and SD according to SP for both age groups in Experiment 2.*

	Younger (N = 35)				**Older** (N = 35)			
	Unimodal		**Crossmodal**		**Unimodal**		**Crossmodal**	
	M	SD	M	SD	M	SD	M	SD
SP 1	.59	.19	.55	.20	.53	.19	.51	.19
SP 2	.59	.21	.50	.15	.44	.18	.50	.23
SP 3	.72	.20	.74	.18	.61	.18	.71	.17

Table 3 *– Mean accuracy and SD as a function of SP for AD patients and OA2 in Experiment 3.*

	AD (N = 24)				**OA 2** (N = 24)			
	Unimodal		**Crossmodal**		**Unimodal**		**Crossmodal**	
	M	SD	M	SD	M	SD	M	SD
SP 1	.40	.18	.42	.20	.89	.06	.83	.12
SP 2	.48	.16	.58	.18	.82	.10	.86	.09